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THE ROLE OF CONDITION MONITORING

IN MAINTENANCE MANAGEMENT

J. R. Mossner

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I, Johan Richard Mossner , submit this thesis in partial fulfillment of the requirements for the degree of Master of Science in Engineering. I claim that this is my original work and that it has not been submitted in this or in a similar form for a degree at any University.

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ABSTRACT

By outlining the role of CONDITION MONITORING in Maintenance Management strategies,and the numerous advantages attainable, this thesis creates a basis for further research into the applicability of CONDITION MONITORING to South African Industry.

Maintenance operations can be split into three basic categories. These are Corrective (breakdown), Preventive (regular) and Predictive (condition based) Maintenance strategies. Nowadays corrective maintenance is often no longer a viable approach due to the disadvantages associated with catastrophic failure. Usually machines are attended to and attempts made to avoid breakdowns by periodic maintenance. This is not an ideal solution since unexpected failures will still occur. Often interfering with a smoothly running machine can have an adverse effect on the machine's performance. Predictive maintenance, on the other hand allows machines to be run "the last mile" by only repairing them when and where faults are detected, or at a convenient time.

Thus a condition-based maintenance system will reduce the number and severity of failures and hence costs. Reduced downtime, smaller maintenance teams, increased production and lower insurance costs all combine to make such systems extremely attractive. Condition monitoring is also essential where increased production requirements lead to faster machine speeds making downtime costly and failures dangerous to personnel. Unfortunately the cost of CM equipment is in direct proportion to the amount of warning required. However, the benefits far outweigh the costs, and predictive maintenance systems can be expected to recover their costs within two years.

Condition monitoring can be split into three main categories, namely Wear Debris Monitoring (WDM), Component and System Performance Monitoring (CSPM), and Vibration Monitoring (VM). WDM judges machine condition by inspecting machine fluids for deposited debris, suspended debris and oil condition. The nature of the debris gives an indication of the source and cause of irregularities.

CSPM looks at the general operating characteristics of machines and systems. Any faults will show up in the output of the system as a decreased efficiency or faulty products. eg A blocked pressure relief valve would be indicated by a build-up in

temperature and pressure. These two techniques are fairly straightforward and have been in use for a while.

Vibration Monitoring , on the other hand, has been the subject of much research and development in the last decade. By analysing the vibration patterns from machines, faults can be detected, pinpointed, and diagnosed before failure occurs. Areas that have recieved attention are the technology involved, diagnostic techniques, and the application of these techniques to practical maintenance activities.

VM has many applications, since it can be used on virtually any moving machinery. One of the major problems associated with VM is that the measured signal is invariably corrupted with noise from other machines and components. Hence a lot of work is beeing done on improving the Signal to Noise Ratio (SNR) in vibration signatures. SNR techniques such as Signal Averaging, Adaptive Noise Cancelling, Filtering, Resonance techniques and Cepstrum Analysis have been successfully used in many applications. Cepstrum Analysis is a specialised method of analysing vibration spectra by detecting harmonic components. It can be used to detect and diagnose faults in a wide variety of rotating machinery.

The elementary tool of the Predictive Maintenance Engineer is the vibration spectrum, which gives the frequency content of vibration signals. It can be used on its own in simple systems, or in conjunction with other signal analysis techniques. Fault diagnosis can be based on a time signal, Vibration Level Standards or statistical data analysis techniques. Some of these methods are more effective than others, but they all have some value since different faults are hihglighted in different ways. Often it will require two or more methods to cover all types of failure patterns on a particular machine.

When setting up for Condition Monitoring various consideration need to be made such as machine selection, monitoring methods, an introductory programme and level of automation. Because of the large volume of data and the complex diagnostic techniques involved, computers play an important role in Predictive Maintenance systems. With the increasing complexity , cost and availability of plant machinery in South Africa, Condition Monitoring is destined to become an essential part of Maintenance Management Techniques.

GLOSSARY

BAND-PASS FILTER - a wave filter that has a single transmission band between two cutoff frequencies.

FOURIER TRANSFORM - periodic functions may be represented by a Fourier series which consists of a sum of sine waves whose frequencies are all multiples of the fundamental frequency.

FAST FOURIER TRANSFORM (FFT) - a computer algorithm for calculating discreet fourier transforms from digitised time signals.

HARMONIC - a sinusoidal quantity having a frequency that is an integral multiple of of the frequency of a periodic quantity to which it is related.

MODULATION - the variation in the value of some parameter which characterises a periodic oscillation (eg. frequency).

NOISE - any unwanted disturbance within a useful frequency band.

POWER SPECTRAL DENSITY - the limiting mean square value of some parameter of a signal per unit bandwidth .

ROOT MEAN SQUARE (RMS) - the square root of the time average of the square of the function

SHOCK PULSE - a substantial disturbance characterised by a rise of acceleration from and a decay back to a constant value in a short period of time.

SPECTRUM - the definition of the magnitude of the frequency components that make up a signal.

TRANSDUCER - a device that converts shock or vibratory motion into a signal that is proportional to the magnitude of the motion.

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1. INTRODUCTION

There are three basic maintenance strategies which can be applied to a typical engineering plant. These are Breakdown, Preventive and Predictive maintenance systems'. Until recently breakdown and regular preventive maintenance systems have been used most often, but they are steadily being phased out by condition based maintenance. Not that they will ever be discarded completely, since each has a place in industry. There are however, distinct advantages in using predictive maintenance techniques. The decision to shut down a plant is an onerous one, and mistakes can be costly, but the costs of ignoring the signs can be much higher.

A maintenance system that can accurately monitor the condition of equipment can cut costs and increase productivity by taking the guesswork out of shut-down decisions. The number and severity of failures can be reduced, with corresponding reductions in downtime, insurance costs and spares. Problems that are not serious can be schedules for repair during routine shut-down periods. Condition based maintenance is ideal for components that fail progressively rather than suddenly. This applies to most mechanical equipment, and since failures do not occur at regular intervals, condition based maintenance is inherently more logical than regular maintenance, which is more suited to components that fail suddenly.

Condition monitoring techniques can be split into three main categories:

1. Wear Debris Monitoring
2. Component and System Performance Monitoring
3. Vibration Monitoring

All of these are suited to one application or another. There have been major developments, in vibration monitoring in particular, in the technology and in the matching of the measurement techniques to the needs of practical maintenance activities. One of the reasons for this is the wide range of machines and faults that are suitable for the application of vibration analysis. It can be used to detect malfunctioning valves in compressors, damaged bearings, faulty gears and misaligned disk couplings, to name a few.

The objectives of this thesis are to explain what vibration monitoring entails and how it can be used to detect and diagnose faulty components, and to show that it is an indispensable tool for maintenance engineers.

2. INTRODUCTION TO MAINTENANCE TECHNIQUES

Effective maintenance of a plant and its equipment is a pre-requisite to efficient plant operation and uninterrupted production. Traditional machinery maintenance practice in industry can broadly be categorised into three categories: Corrective, Preventive and Predictive or On-Condition Maintenance.

Corrective Maintenance has been defined as that which is carried out when equipment fails or falls below an acceptable condition during operation. It is applicable in industries running many inexpensive machines and having each important process duplicated. Here machines are repaired as and when they break down. Loss of production and costs incurred will not be significant, as spare machines can usually take over while the fault is repaired. In this situation the machines are relatively simple and breakdowns easy to repair. Consequently there is usually no economic or safety advantage in knowing when breakdowns will occur or in trying to prevent their occurrence. However, in some industries it is not possible to provide back-up machines. In such cases it is essential to minimise failures since breakdowns are expensive in direct repair costs and consequential lost production. Malfunctions need not be in the form of breakdowns to be expensive; with the high production rates common today a change in conditions can result in a huge number of defective products in a very short period. Consequently Preventive and Predictive maintenance play an important role in efficient plant operation.

Where important machines are not fully duplicated or where unscheduled production stops can result in large losses, planned maintenance operations are often performed at regular intervals. Here a definite programme of periodic cleaning, servicing, inspection, and replacement of worn parts is followed. This in itself is not an ideal system, since unexpected failures will still occur. Another factor is that the failure rate of many machines is not improved by replacing parts regularly. On the contrary, the reliability of newly serviced machines if often reduced by human interference. When a failure does occur, the cause is usually investigated and statistical records kept to indicate changes in pattern of failure and analysed to provide a basis for modification to the maintenance program. Preventive Maintenance theory suggests that if enough information is available it would reveal what the effective working life of the particular component was. For simple items of equipment this theory holds true, thus the component can be replaced shortly before it is destined to fail.

However, in the case of complex equipment, research has revealed six different patterns of failure which predict the probability of a machine failing and are summarized in Figure 2.1 overleaf[2]. The basic difference between the failure patterns of complex and simple items has important implications for maintenance management. The first and most important point to emerge from this is that in most industries the concept of regular scheduled overhauls of complex equipment is not only obsolete but actually counter-productive.

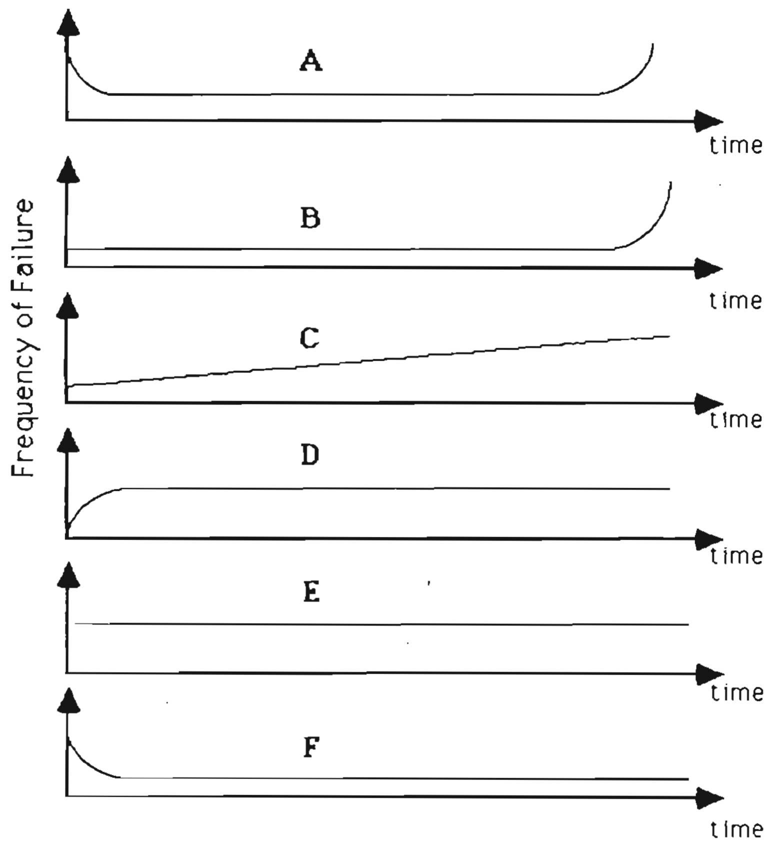


Figure 2.1 Theoretical Failure Patterns

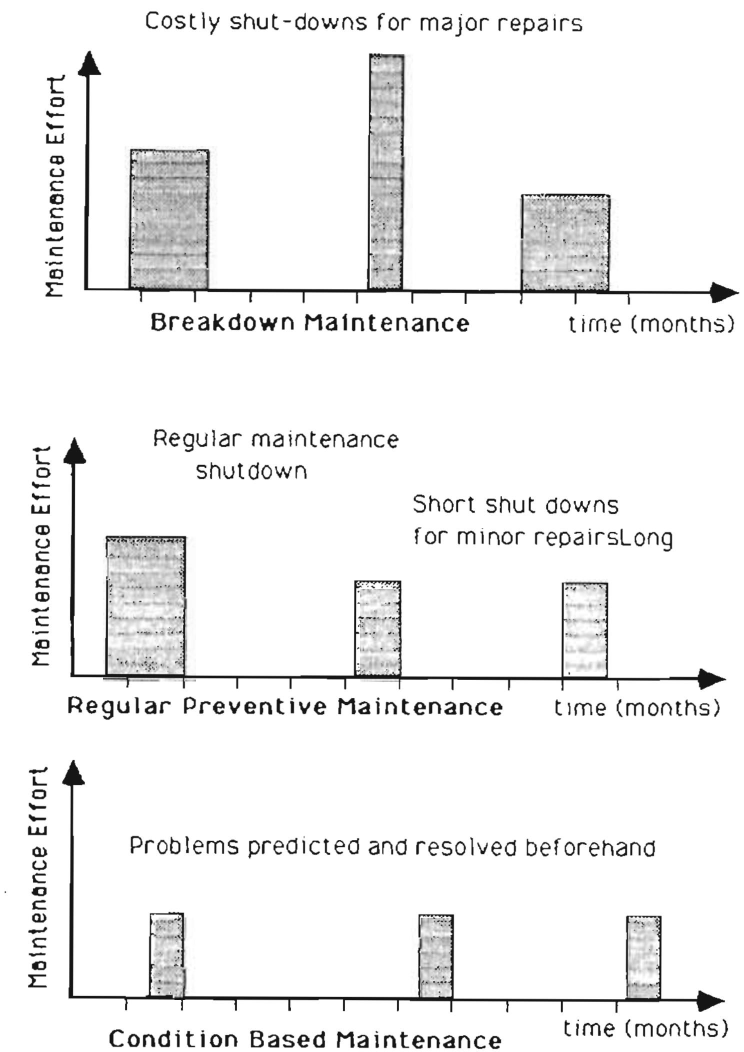


Figure 2.2 Results of Maintaining Plant by different Methods

Secondly, the relatively large number of complex items which fail on a random basis has led to a move away from trying to establish fixed time intervals at which scheduled rework or replacement of components should be carried out. Instead there is an increasing trend towards inspection procedures designed to establish when and where failures are initiated. Nowadays a great deal of time is being devoted to finding potential failure conditions which give as much warning as possible of functional failures. Obviously the more warning there is of a functional failure, the more time there is to rectify it at a convenient time.

The techniques designed to detect the existence of potential failures are known generally as condition Monitoring techniques. Some of these techniques can give several months warning of failure. Unfortunately the cost of the system usually increases in direct proportion to the amount of warning required. The most important of these techniques are vibration analysis and oil analysis since most machines have moving parts that generate vibration as well as parts with relative motion in contact with another, generating wear debris. There is also considerable scope in component and system performance monitoring, by using existing control instrumentation for monitoring functions of machines and components. Here the components and systems are monitored for overall performance to detect faults.

It is generally desirable, where possible, to use two monitoring methods simultaneously to monitor any critical machine. This improves the certainty in detecting the existence of a potential fault. Two methods are also used to prevent false alarms due to measuring equipment malfunction or false interpretation of information.

3. CONDITION MONITORING - GENERAL

3.1 General Aspects of Condition Monitoring

The basic principle of condition monitoring is to select a suitable measurement, or measurements, which are sensitive to component deterioration. Regular readings of these measurements will then point out any deviation or trend that would indicate the existence of a problem. By carefully extrapolating the trend curve, an indication of the time to failure, or lead time can be obtained. Maintenance can then be scheduled for a convenient date.

It is important to determine the minimum time to failure of a component with respect to the level of measured parameter. For this to be successful, the period between measurements must be less than the minimum time for a parameter to reach a dangerous level. During its early life period, a machine should be carefully monitored since probability of failure is high initially, decaying as the machine is run in. The time between measurements may be increased once the trend curve stabilizes, and later decreased when a definite deterioration in machine condition is detected or warning levels are reached. The maintenance engineer could then schedule the repair work for a convenient time, or he could delay it to coincide with planned down-time if conditions permit.

An important feature of condition monitoring is that the monitored activity operates at two levels:

1) The detection of potential problems (diagnosis)
2) The determination of the exact nature of the problem (prognosis)

The first aspect can be dealt with by reliable routine work at a relatively low level, or could even be handled automatically. The second aspect is a skilled professional operation requiring considerable experience and a detailed knowledge of the machine construction[3].

3.2 Circumstances Affecting the Application of Condition Monitoring

There are also various operational circumstances in a company which may tend to favour or go against the application of condition monitoring. These are summed up below'.

Favourable Circumstances

Situation	Application
1. Where a safety risk is likely to arise from the breakdown of machinery.	Plant handling dangerous materials, and machines involving the transport and safety of people.
2. Where accurate and advanced planning of maintenance is essential.	Remotely situated equipment, and mobile (out of base) equipment.
3. Where plant or equipment is of recent design and may have residual problems	Condition monitoring enables faults to be detected early while damage is still slight, and so can guide design improvements.

Situation	Application
4. Where operators cannot be expected to detect faults in expensive equipment where breakdowns are costly.	Condition monitoring enables faults to be detected early enough to prevent damage by withdrawal and/or repair of the equipment.
5. Where the manufacturer can offer a condition monitoring service to several users of his equipment.	The cost to each user can be reduced, and the manufacturer gets useful feedback to guide design and development.
6. Where equipment or instruments required for condition monitoring is already being used for another purpose.	Other applications of the instruments or equipment may be process control or some servicing activity such as rotor balancing.
7. Where important equipment is used that is not duplicated.	In some processes it is not possible or not viable to duplicate essential equipment.

Unfavourable Circumstances

Situation	Application
1. Where an industry is operating at a low level of activity and plant and machinery is idle or duplicated.	If the plant is only operating part of the time there is enough opportunity for maintenance and inspection during idle periods.
2. Where the number of machines is too small to enable sufficient experience to be gained for effective interpretation of information.	The problem may be overcome by pooling monitoring services with other companies or by contracting the monitoring work out to external services
3. Where skilled operators have close physical contact with their machines and can do their own monitoring.	Machine tools and ships are examples where skilled technicians "understand" their machines. Any trend towards the use of supervisory engineers favours the application of condition monitoring.

Situation	Application
4. Where machinery is mobile and specialist overhaul is done at central depots by skilled labour.	In such a situation condition monitoring could be used to establish overhaul priorities for various units. Condition monitoring is not worthwhile unless improved machine design and performance is achieved in the long run.

On-condition maintenance based on vibration monitoring can be employed successfully by achieving substantial savings owing to higher availability of production machinery and the corresponding increase in productivity. The benefits which arise from condition monitoring are summed up in the following table'.

Benefits derived from plant condition monitoring	How these benefits arise:
1. Increased plant availability and productivity	- Machine Running time is increased by maximising time between overhauls. - Virtual elimination of unexpected breakdowns. Overhaul time is reduced since the nature of the problem is known, and the spares and men can be ready.
2. Reduced Maintenance Costs	- Elimination of secondary damage. - No scrapping of serviceable components - Cost of storing fewer replacement parts is decreased. - Smaller maintenance crew required.

Benefits derived from plant condition monitoring	How these benefits arise:
3. Improved operator and passenger safety	- The lead time to failure means that potential break-downs can be averted.
4. More efficient plant operation and more consistent quality obtained by matching the rate of output to the plant condition.	- Reduction of spare part stock by fore-warning. - Operating conditions may be varied to obtain a better compromise between output and operating life to the next overhaul.
5. More effective negotiations with equipment manufacturers	- Measurements of equipment when new and after overhaul give good comparative values.
6. Better customer relations by meeting schedules without undue interruption.	- Forewarning of major problems allows for negotiations between producer and customer.

Benefits derived from plant condition monitoring	How these benefits arise:
7. The opportunity to specify and design better equipment in the future.	- Recorded information allows future faults to be avoided by correct design and application of equipment.
8. Reduction in business interruption savings on insurance premiums.	- Damage insurance and lost production insurance premiums are reduced due to reduced risk.
9. Increased rate of net output.	- Some types of machine may be run at increased load or speed. - Increased energy consumption or reductions in machine efficiency can be detected.

4. CONDITION MONITORING TECHNIQUES.

The main techniques used for the condition monitoring of plant and machinery are tending to concentrate into three areas which are vibration monitoring, wear debris monitoring (including corrosion debris) and component and system performance monitoring[4]. There have been numerous developments in these areas in the diagnosis and prognosis of faults, and also in the matching up of the measurement techniques to the needs of practical maintenance activities.

4.1 Wear Debris Monitoring

Parts of machines which move relative to each other tend to generate wear debris from their interactions. The effects are particularly pronounced if the operation is not smooth or if the surfaces are highly stressed and thus prone to local fatigue or pitting. If the components are flushed with fluids such as lubricating oils or coolants, the wear debris that is generated tends to be carried away and can thus be extracted at a convenient time and place. By examining the quantity, type and shape of the wear debris, useful information can be obtained on the source of the debris and the condition of the components. Contaminant analysis can cover the debris deposited, the debris in suspension or the condition of the oil[4,5,6,7].

4.1.1 Deposited Debris:

The larger particles carried in the lubricant can be collected with the machine still on-load by means of filters or magnetic collectors.

(a) Filters -
The rate of build-up of debris in a filter can readily be determined by measuring the pressure drop across the filter. If the system is suitably designed, the filter can be removed without run-down. The particles are then examined under a microscope to establish the quantity (severity of stress conditions) and the shape and size of the particles (source). Spectographic analysis may also be carried out to determine the element content. The debris may be stored on an adhesive surface for record keeping purposes.

(b) Magnetic Collectors -
This is a convenient way of collecting ferrous debris. They can be designed to be removed on-load and some of them may be monitored without removal giving an indication of debris build-up.

4.1.2 <u>Debris in Suspension</u>:

Sub-microscopic particles carried by the lubricant will remain in suspension. The examination of suspended particles gives the earliest warning of failure. Quantitative measurements may be used (eg. parts per million) but account must be taken of the dilutive effect of topping up with debris free oil.

(a) Spectrometric Oil Analysis (SOA) -
SOA uses either an emission or an atomic absorption spectrometer to measure the analytical "spectrum" of a sample by measuring the concentrations of various elements such as Copper and Lead. It provides only information on concentration and composition of debris, and no information on the shape of debris.

(b) Ferrographic Oil Analysis -
Here magnetic particles are deposited onto a substrate according to size. The particles may then be subsequently examined for concentration, size and shape.

4.1.3 Condition of the Oil

The oil itself can be examined more generally for indication of other malfunctions. Some typical indications and their causes are listed below:

Indication	Cause	Action
Foaming	Excess churning or passage under pressure through a restriction.	Check system
	Detergent Contamination	Check seals and gaskets.
Emulsion separates out naturally	Water	Drain off water
Emulsion separates in centrifuge	Water	Change oil
Colour darkened	Oxidation of oil, over-heating. Combustion or other products reaching oil	Check system and change oil

4.1.4 Application of Wear Debris Analysis

The different methods tend to be suitable for different machine components. Magnetic plugs are relatively ideal for monitoring the condition of ferrous components. good examples are roller bearings and gears which produce ferrous debris as a result of surface pitting. The size of the particles causes them to settle out and not remain suspended in the solution. and so extracted oil samples will not be useful.

Spectrographic oil analysis is better for detecting smaller particles which remain in suspension in an oil sample and tend to derive from conforming bearing surfaces such as plain bearings. piston rings and cylinder liners.

Ferrography is intermediate and partly overlapping between these two methods in terms of particle size. It is useful for detecting the wear mechanisms that are operating by microscopic examination of the particles after magnetic separation from the oil sample.

The usual method of utilising information gleaned from wear debris techniques is to plot the measured parameter(s) on a particle count versus time graph (trend analysis). The onset of failure by fatigue or other method is indicated in the form of a sharp rise in the curve. Since damage is self propagating. the trend curves usually show exponential increases with the development of the failure. The trend curves will usually demonstrate the "bathtub" type of failure curve since during running-in the debris collection rate will reduce with time. remain constant during normal life and then increase at the onset of failure[2,5].

When a change occurs, knowledge of the change in composition will assist in determining which component has changed:

Normal wear	-	flat particles
Abrasive wear	-	spiral shaped debris
Ball damage	-	rounded "rose petal", radially split shape.
Track wear	-	rounded, surface break up, criss cross scratches.
Roller damage	-	generally curled and rectangular, with parallel lines across width.
Gear tooth damage	-	irregular shape, grey surface.

The use of spectrometry or ferrography provides additional information which assists in pinpointing the damaged component.

4.2. Component and System Performance Monitoring

In this method components and systems are monitored to ensure that they are performing their required function[1,4]. The philosophy of this principle is a logical follow-up to the instinctive ability of the average motorist to observe changes in performance such as noises, unusual vibrations, increases in fuel or oil consumption and leaking joints. The simplest and most common type of examination is visual, using instruments such as image-intensifiers to light up dark areas, fibre-optics to examine inaccessible corners and dye penetrant techniques. Visual inspection is a powerful technique because of the effectiveness of the human eye. The main disadvantage is that data recording is not always quantitative and hence trend monitoring is difficult.

Thermal monitoring also plays an important part in performance monitoring'. Monitoring the temperature of a component in a machine is undertaken for one of three purposes.

(1) To enable the temperature of a process to be controlled manually, or to check that it is being controlled correctly.

(2) To detect an increase in heat generation due to a malfunction such as a damaged bearing.

(3) To detect the change in heat transmitted through and out of a machine or component caused by a malfunction.

Temperature monitoring devices can broadly be split into three categories: contact sensors, non-contact sensors and thermographic compounds.

Contact Sensors

(a) Liquid Expansion Sensors:
Most commonly used devices. Mercury or alcohol in glass thermometers are accurate but fragile. Since the sensors are relatively large they are unsuitable for surface measurement.

(b) Bimetallic Sensors:
Can be made compact and robust. They are unsuitable for surface measurement, but can be used to measure high temperatures.

(c) Thermocouples:
These are small and versatile and can be used to measure surface temperatures.

(d) Resistance Sensors:
The change in resistance of an element with temperature is used to determine temperature. The temperature range is limited to about 300°C and the resistance tends to drift with age, requiring rezeroing.

Non-Contact Sensors

(a) Optical Pyrometer:
Above 500°C radiation is in the visible range. The colour of the gas or body gives an indication of the temperature.

(b) Radiation Pyrometer:
Thermopiles or lead-sulphide cells are used to measure the radiant energy received from a hot surface in the range 50 - 4000°C.

(c) The Scanning Infra-red Camera:
These units cover a temperature range of 20 - 2000°C. Although expensive the devices can give a resolution of 0.2°C at 20°C.

Thermal imaging is an effective method for detecting temperature irregularities in turbines, bearings, furnace linings and pipelines. An infra-red scanning unit with a cathode ray monitor producing an image of the radiating source will indicate malfunctions by showing up as bright spots (leaks, defective insulation) or dark areas (obstructions).

For pressure vessels and piping carrying corrosive fluids, corrosive monitoring and wall thickness measurements can be used to indicate any impending risk of rupture. A simple technique is to use small sentinel holes in the pipe which will indicate when the corrosion reaches the bottom of the hole, which is subsequently blocked[4]. Removable coupons made of component material are also used in the fluid stream. By removing and weighing them at regular intervals, the corrosion rate can be estimated. In some cases the corrosion rate can be determined by measuring and recording the electrolytic current on a watt-hour meter or similar instrument.

Systems can be monitored by checking their overall performance and by comparing one characteristic with another. In the case of motor vehicles fuel consumption could be used to show up any defect. In the case of pumps the delivery flow and pressure indicate the component's condition. This technique of comparing parameters is useful in that data can be recorded graphically and trends monitored. However, since no two machines are identical, care must be taken when analysing comparative data.

System performance monitoring techniques tend to be specific to a piece of plant, and for this reason there is less proprietary equipment available on the market for carrying out this kind of monitoring. Thus there is greater scope for effective individual methods to be developed by the engineers concerned in each case, and tailored to meet specific requirements.

4.3. <u>Vibration Monitoring</u>

This is probably the oldest form of condition monitoring[5,7,8,9]. Most people have come across it without even realising it. A change in the sound of a car's engine, or in a moving machine can cause concern and is usually followed by a period of close examination to try to find the cause of the problem. This is vibration monitoring in its simplest form. In the past plant engineers involved in the running and control of machines learnt to recognise by touch and hearing whether a machine was running smoothly or whether a fault was developing. The days of plant attendants with an oily rag, a grease gun at hand and a screwdriver held to the ear to pick up vibrations are gone. The reason is that the personal relationship between man and machine is no longer economically feasible and is unreliable on the expensive and sophisticated high speed machinery of today: many of the tell-tale vibrations occur at such high frequencies that instruments are needed to detect and measure them.

Why do vibrations occur? In practice, vibration occurs as a by-product of the transmission of energy through a mechanism. Machine elements react against each other and energy is dissipated through the structure in the form of vibration. A good design will produce low levels of inherent vibration. As the machines wear foundations settle, parts deform and wear, rotors become unbalanced and clearances increase. These factors are reflected in an increase in vibration energy which excites resonances and puts considerable extra dynamic loads on bearings as it is dissipated throughout the machine. Cause and effect reinforce each other, and the severity of the faults invariably increase exponentially as the machine progresses towards ultimate breakdown.

A vibration signal has several elements. Amplitude is always a valid measure of the severity of an anomaly. The frequency at which the vibration occurs indicates the source or type of anomaly causing the vibration. Other elements that are useful in vibration analysis are time between periodic occurrences and spacing between related frequency components. As long as the excitation forces within a machine are constant, or vary within certain limits, the vibration level measured will also be constant or vary within similar limits. Furthermore for most machines, the vibration has a typical level and its frequency spectrum has a characteristic shape when the machine is in good condition. This frequency spectrum, a plot of vibration amplitude against frequency, is known as the vibration signature of the machine, and is obtained by frequency-analysing the machine vibration signal. The fact that vibration signals carry much information relating to the condition of running machines is the basis for using regular vibration measurement and analysis as an indicator of machine health trends and the need for maintenance.

4.4 Progress in Condition Monitoring

Component and System performance monitoring is by far the most straightforward technique in Condition Monitoring. If something is not functioning properly, there will be a change in the desired output of the item which will give a direct indication as to the cause of the problem. All that is required is the correct instrumentation and monitoring, followed up by a logical diagnosis of the problem. The only recent major advances in this field have been improvements in existing instrumentation and techniques, with few (if any) new techniques being developed.

Wear Debris Monitoring is similar in that there have been no recent major developments in diagnostic techniques. The amount of information that can be extracted from wear debris analysis is also limited, and so the only developments in this field have been in improving the methods of extracting this information.

Whereas spectometric oil analysis and particle examination procedures have stayed the same, there have been developments in improving and increasing the sensitivity of instruments that automatically determine the amount of debris in solution, thus eliminating the need for tedious manual intervention and allowing for measurements to be taken on-line.

Vibration monitoring, on the other hand, has been the subject of much research and development over the last decade. Problems that have to be overcome are signal interpretation, noise reduction, handling large amounts of information, and improvements in frequency analysis techniques. The introduction of the micro-computer has also had an important effect on the development of signal analysis and it is for these reasons that vibration monitoring is covered in detail in the next chapters.

5. VIBRATION ANALYSIS

5.1 EQUIPMENT USED FOR VIBRATION ANALYSIS

5.1.1 Vibration Transducers

Transducers are an essential part of any measuring system[7,10]. It is thus important to select the correct type to suit each particular application. Transducers fall into three categories, determined by the parameters that they measure:

(1) Displacement transducers
(2) Velocity transducers
(3) Accelerometers.

The construction of these instruments affects their frequency response and hence their applicability in various circumstances. Relative displacement transducers such as eddy current or proximity probes have a frequency range that can extend up to 10000Hz. However, they are more suitable for detecting low frequency components since the higher harmonics usually fall outside their limited dynamic range.

Siesmic transducers, on the other hand, have proved to be far more suitable for general machine condition monitoring duties. The most widely used seismic transducers are the velocity pickup and the piezo-electric accelerometer. Piezoelectric transducers have in recent years become the most popular because of their superior frequency and dynamic ranges, smaller dimensions and their long-term reliability. The main drawback of any transducer operating on the piezoelectric effect is that the motion is converted into a charge which is dissipated in the signal conditioning equipment and the cable. If the rate of change of motion is slow this dissipation affects the reading and places a low frequency limit on the range of the device. Modern amplifiers with input impedances up to 100 GΩ enable measurements to be made of frequencies as low as 0.1Hz. The relative responses of transducers is shown in figure 5.1.

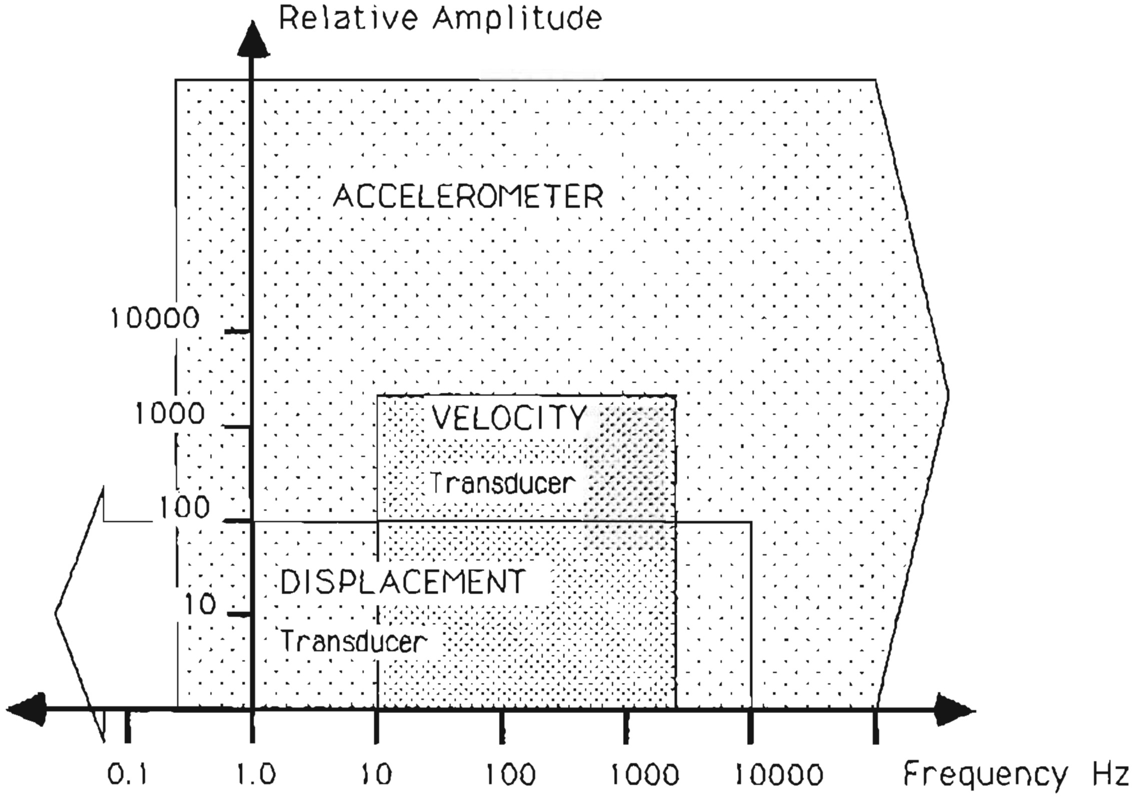


Figure 5.1 Transducer Characteristics

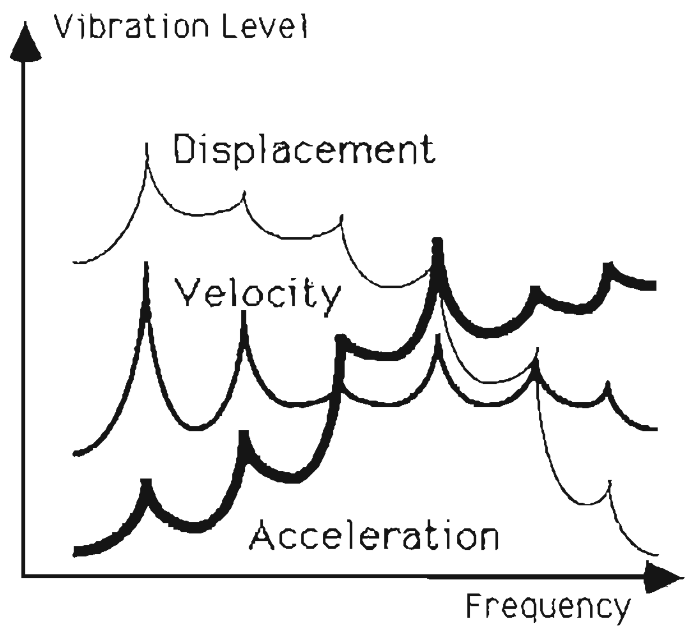


Figure 5.2 Typical Vibration Spectra

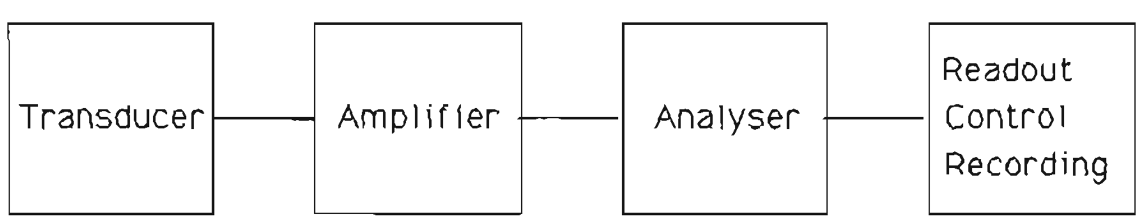


Figure 5.3 Typical Instrument Chain for Machine Analysis

An added advantage in using an accelerometer is that the measured parameter (acceleration) can easily be converted to velocity or displacement by simply integrating the acceleration signal. On an Amplitude - frequency plot the three curves will exhibit peaks at the same frequencies and the amplitude of the peaks relative to the general slope of each spectrum will be the same (see figure 5.2). The simple mathematical relationship between the curves allows the value at any frequency to be converted to a value at the same frequency at any of the other curves. When recording measured signals, acceleration is usually recorded to allow for simple conversion to velocity or displacement if required. In general, it is desirable to monitor the parameter with the flattest response curve as this gives a higher signal to noise ratio. Frequency components on such curves also need a smaller relative change before they affect the overall wide-band vibration level.

5.1.2 <u>Instrumentation Systems.</u>

There are four basic components in any measuring chain used for machine analysis, and they are associated with the measurement, amplification, conditioning, and display of the signal. These components are shown schematically in figure 5.3. Such systems vary from simple hand-held meters to sophisticated computer-controlled permanent monitoring equipment. They systems can be classified into three levels of sophistication, and it is reflected in their speed, the time taken and information provided for locating faults, and how accurately tho time to ultimate failure can be predicted. These three systems are:

(a) A simple manual system consisting of a hand-held vibration meter that measures the broad-band vibration level over a wide frequency range. Measurements are compared with general standards or established reference levels, and are recorded manually by the operator.

(b) Using frequency analysis it becomes possible to diagnose and predict breakdowns at an earlier stage. Portable equipment allows narrow band frequency analysis and a spectrum plot to be performed on the spot for each monitoring point. The levels of certain frequency components can be plotted on trend curves to enable faults to be diagnosed before breakdown occurs.

(c) With large number of monitoring points, a computer aided spectral analyser may be employed. Vibration measurements can be collected on a tape recorder or may be fed directly into the system via a permanent monitoring network. Computer programs and fault diagnosis and trend monitoring, and large quantities of data can be stored. The program package can include programs for advanced analysis techniques such as cepstrum analysis, trend predictions, harmonic and sideband cursor programs and many other newly developed techniques. These techniques will be covered in Chapter 6.

5.1.3 <u>Spectral Analysers</u>

The most important elements of the spectral analyser are the filters or filter systems. There are generally two types of filter systems:

(a) Constant percentage band width (octave band, one-third octave band, etc.

(b) Fixed bandwidth.

The constant percentage bandwidth analyser has a bandwidth which is a constant percentage of the band centre frequency. The octave band analyser (OBA) is the simplest of these analysers, and separates the spectrum into bands one octave wide. Thus at low frequencies the filter band width is only a few hertz wide, ranging to thousands of hertz wide at high frequencies.

Fixed bandwidth analysers provide a constant narrow bandwidth over the entire tuning range. the main limitations of these filters are as follows:

- long data acquisition sweep or tuning times
- difficulty in maintaining stable frequency calibration
- usually large and not portable.

In spectral analysis the filters are used to pass only the interesting parts of the spectrum. The signal passing each filter can be amplified or attenuated to increase or reduce its importance in the graphic display or at a level detector. The filters play an important role in automatic monitoring systems. They can be used in parallel to act on the same level detector, or they could be connected to different level detectors with varying alarm settings. thus monitoring systems can be built up to monitor wideband vibration levels, or in more complex systems, 1/3 octave or narrower frequency band monitoring can be employed to monitor specific frequencies.

5.2 THE VIBRATION SIGNAL

5.2.1 Describing the Amplitude of a Signal

A measured signal, whether it be acceleration, velocity or amplitude, could have any one of four forms':

(a) Pure sinusoidal such as that generated by an unbalanced rotor. This signal has only one frequency component as shown in figure 5.4(a). The size of the signal could be described by either the peak value or the root mean square value since for a sine wave $V_{peak} = \sqrt{2}\, V_{rms}$.

(b) Periodic but non-sinusoidal, containing many discreet frequency components. The repetition period of the signal corresponds to the lowest or fundamental frequency component (f_o in figure 5.4(b)). The total mean square of the signal is equal to the sum of the mean squares of the discreet frequency components. This concept of addition of mean square components plays an important part in frequency analysis.

(c) Random signals, that never repeat themselves exactly. This type of signal is generated by moving contact between solid surfaces. Theoretically the peaks reach infinity for infinitesimal periods. In practice however, such signals have an upper limit, and thus they can be described by their r.m.s. value and their frequency spectrum, which is continuous over a wide frequency range. (see figure 5.4(c))

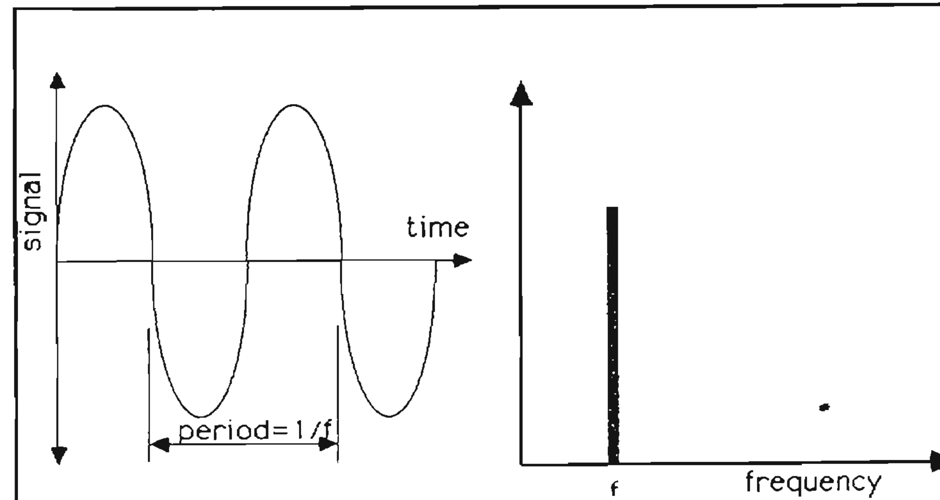


Figure 5.4a Pure sine signal

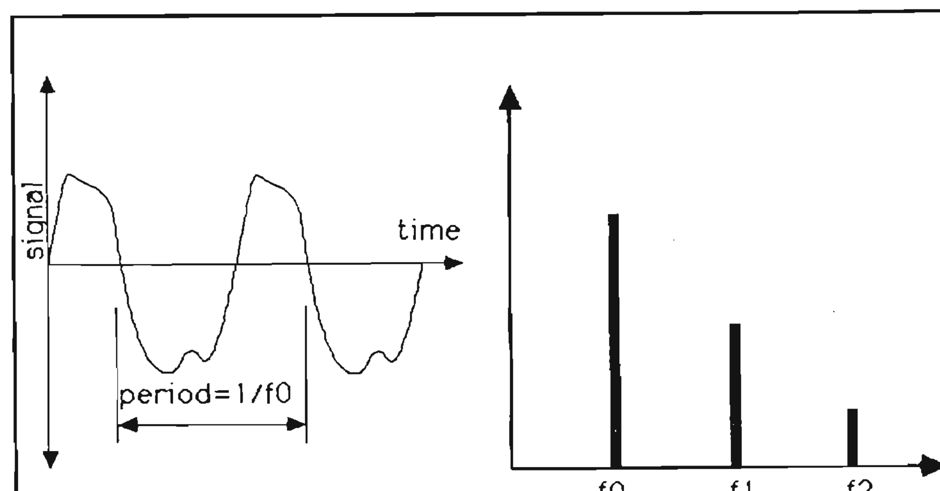


Figure 5.4b Periodic but Non-Sinusoidal

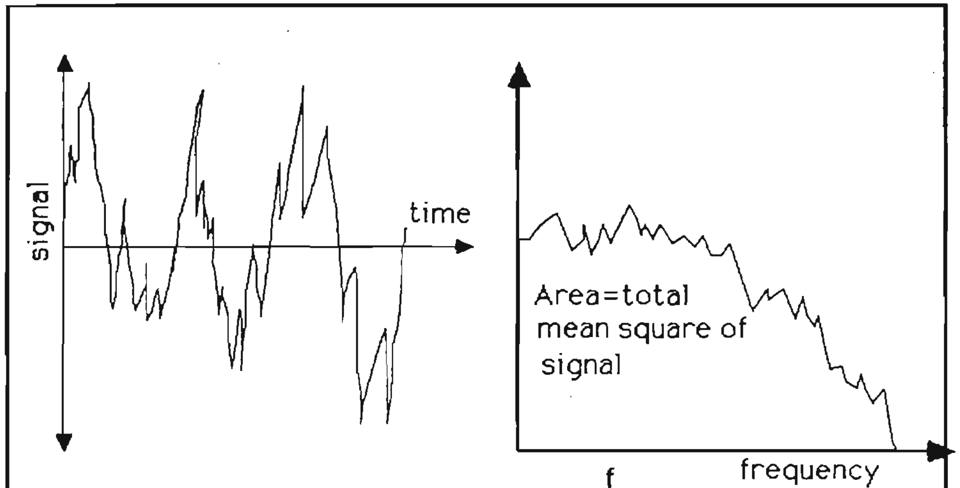


Figure 5.4c Random Noise

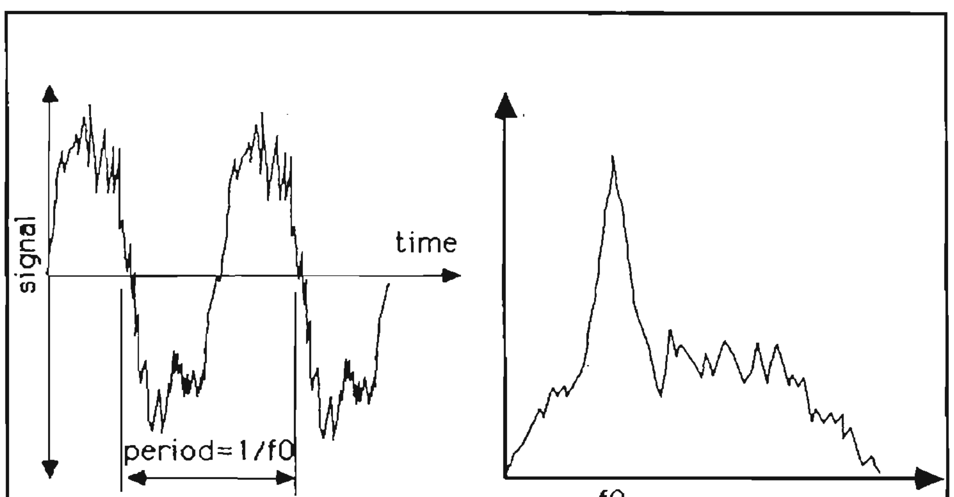


Figure 5.4d Combination of Signals

(d) A combination of sinusoidal, periodic and random such as shown in figure 5.4(d). These are the most often type of signal encountered in vibration analysis and are of interest due to the difficulties involved in interpreting them.

Thus any signal can be described by a measure of its magnitude (eg. r.m.s. time average value) and a measure of its frequency spectrum. The root-mean-square time averaging parameter is the most widely accepted measure of the size of a signal and is defined by the following equation[11]:

$$V_{r.m.s.}^2 = \frac{1}{T}\int_0^T V^2 \, dt \qquad (5.1)$$

where V is the instantaneous value of the signal. The averaging period T must be at least 100 times the length of the lowest frequency component of the signal to get an accurate value for $V_{r.m.s.}$ One of the reasons that r.m.s. time averaging is widely used is that the square of the vibration signal is a measure of the energy content of a signal since kinetic energy is proportional to velocity squared. Thus the r.m.s. value of the signal reflects the mean energy value of the signal.

The size of signals is often given in logarithmic units. This enables large ranges of signal amplitudes to be compressed into small ranges of numbers, while maintaining relative accuracy between components across the range. The logarithmic scale in general use is the decibel scale, which compares the energy (E) to a reference level as follows:

$$\text{Total Energy (dB)} = 10\text{Log}_{10}\,(E/E_{ref}). \qquad (5.2a)$$

Since energy is proportional to the square of the relevant vector quantity (eg displacement, velocity or acceleration) the above equation can be written as:

$$\text{Total Energy (dB)} = 10\text{Log}_{10}\ (V^2/V_{ref}^2)$$

$$= 20\text{Log}_{10}\ (V/V_{ref}) \qquad (5.2b)$$

The decibel is thus a scale relating values, and internationally defined reference levels, for which Total Energy = 0, are given as:

Acceleration	Velocity	Displacement	Sound Pressure
10μm/s	10 nm/s	none	20μPa

The use of a logarithmic scale means that exponential deterioration in a component, if it is similarly reflected in the vibration signal, will show up as equal changes in decibels. By setting an upper limit on the total decibel increase, it then becomes a simple task to linearly extrapolate a dB-time plot to determine when action should be taken.

Another way of using a logarithmic scale for the detection of fault conditions is by comparison of vibration levels with standard criteria such as BS 4675:1976[11] (see figure 5.5) It is defined as "a basis for specifying evaluation standards for rotating machines with operating speeds from 10 to 200 revolutions per second". Emphasis is placed on vibration level comparison rather than absolute criterion levels. This is due to the wide variation of mechanical impedance measured at the bearings of a number of machines in the same class (>10:1). Also, mechanical impedance varies with frequency and thus the use of absolute criteria, applied to overall RMS levels, becomes dubious.

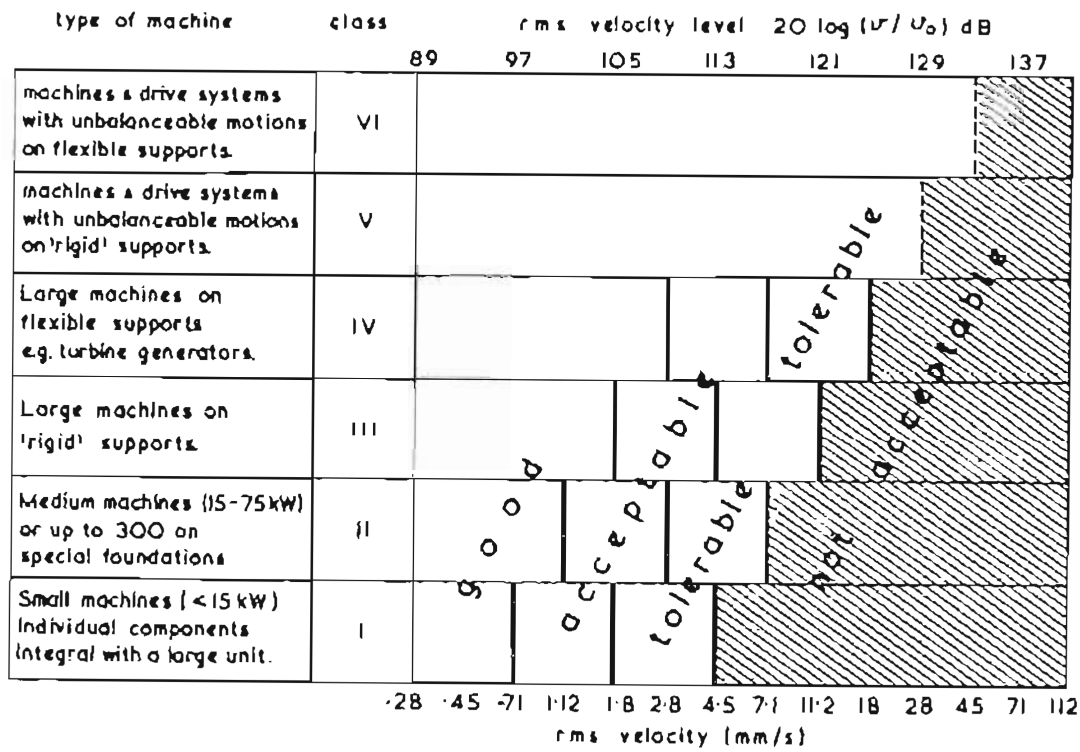


Figure 5.5 Vibration Severity Related to Classification of Machine - BS4675, Part 1, 1976.

A more reliable principle is to use the vibration level when the machine is in good condition as a reference, and to judge machine condition based on changes from the original vibration pattern. This comparison could be done on overall vibration levels or discreet frequency components..

5.2.2 Describing the Frequency of a Signal

Since signals with the same r.m.s. values can have very different waveforms, other methods exist to analyse and describe signals[12,13,14]:

(a) Probability Density Distribution.
The probability that the instantaneous value $x(t)$ of the signal lies within the amplitude range x_1 to x_2 is given by:

$$P[x_1 \leq x(t) \leq x_2] = \int_{x_1}^{x_2} p(x)\, dx \qquad (5.2)$$

where $p(x)$ is the probability density distribution function. The shape of the $p(x)$ curve is useful in identifying harmonic components, normally (Gaussian) distributions, and non linearities in signals. The shapes of such curves are shown in figure 5.6

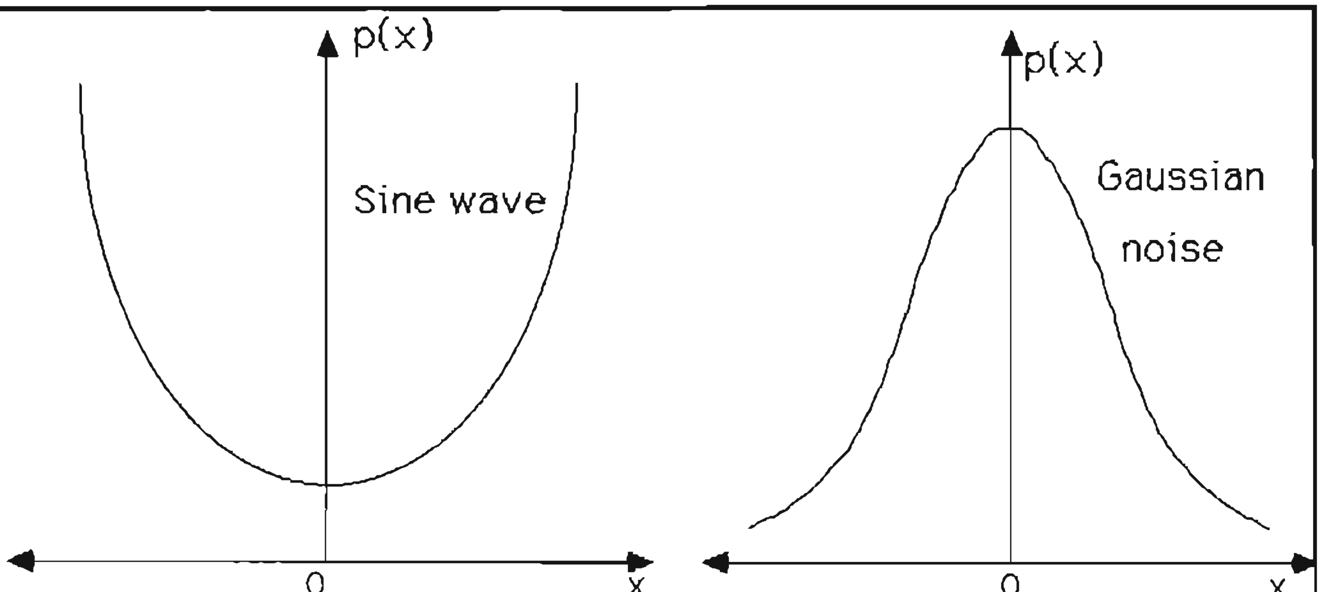


Figure 5.6 Examples of Probability Density Functions

(b) Spectral Density Function

This is the frequency domain representation of a signal, and produces a spectrum that indicates the frequency content of a signal. The signal is represented in the following way:

$$x^2(t) = \int_0^\infty G(f)\, df \qquad (5.3)$$

(c) Auto Correlation Function.

The instantaneous value of a signal is compared to its value a short time away. Thus a function is derived that indicates the typical periods present in a waveform.

$$R(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T x(t)\, x(t+\tau)\, dt \qquad (5.4)$$

The last two functions can be linked through the FOURIER TRANSFORM as follows:

$$R(\tau) = \int_0^\infty G(f) \cos 2\pi f\tau\, df \qquad (5.5a)$$

$$G(f) = 4\int_0^\infty R(\tau) \cos 2\pi f\tau\, d\tau \qquad (5.5b)$$

These relationships are often used to determine $G(f)$, the more physically meaning quantity, from $R(\tau)$ which is easier to measure digitally.

Other, more complex functions exist for analysis purposes, but it suffices to mention that a basic system consists of a transient force $p(t)$, which is modified by an impulse response function $h(t)$ to produce the measured response $x(t)$. This is shown schematically in figure 5.7, with the corresponding Fourier Transforms of the functions. The force-response relation is then

$$x(t) = h(t) * p(t) \qquad (5.6a)$$

$$X(f) = H(f) \cdot P(f) \qquad (5.6b)$$

For further detail on this subject the reader is referred to Clarkson[3] for a more elaborate description of these signal description techniques.

Generally, the direct measurement of spectra is done more conveniently by analogue filters and direct measurement of correlation functions is done more conveniently by digital methods. Although the digital computer is not suitable for the direct measurement of spectra, it can readily compute spectra from a measurement of the correlation function. With the increased use of improved algorithms such as the Fast Fourier Transform (FFT), digital methods are taking over from analogue because of their greater versatility. One of the most significant developments in analysis techniques has been in the application of Cepstrum Analysis to fault diagnosis. This topic is covered in chapters 5 and 6.

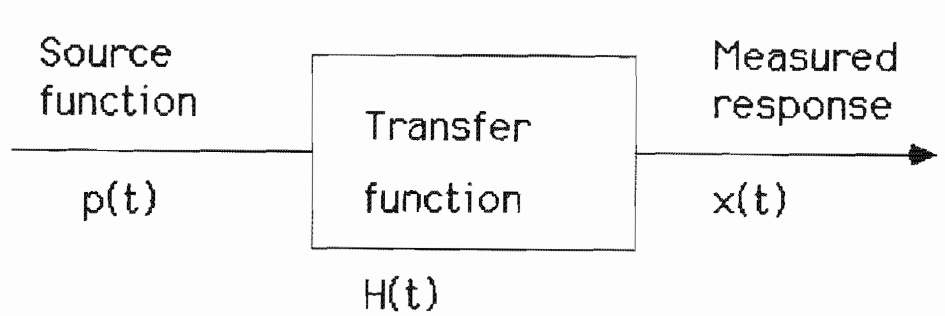


Figure 5.7 Schematic View of Vibration System

5.3 Improving the Signal to Noise Ratio (SNR)

Diagnostics based on vibration signatures are concerned with the extraction of those features from a diagnostic signal which can be related to the machine condition. Signal processing techniques involving time, frequency and statistical analysis can be used successfully to identify faults in simple to complex machines. Fault diagnosis in complex machines like power plant engines and aircraft engines presents a problem due to the excessive background noise that corrupts the machine condition signal. In such cases some method is required to improve the signal to noise ratio (SNR) of the diagnostic signal so that the relevant information can be extracted from the vibration analysis using one or more signal processing techniques. Various methods are available to preprocess the total signal to improve the SNR, and these include:

- Signal Averaging
- Bandpass Filtering
- Adaptive Noise Cancelling (ANC)
- High Frequency Resonance Technique (HFRT)
- Cepstrum Analysis
- Zoom Analysis

5.3.1 Signal Averaging[4,12,15]

This method is also known as synchronous signal averaging. The time signal (digitised) is averaged over a large number of cycles, synchronous with the running speed of a particular gear. This removes background noise and any other periodic events not exactly synchronous with the gear in question, such as mating gears. The process can be repeated for each gear in turn by synchronizing the averaging circuit with the speed of the gear being monitored.

This method has the advantage of giving an accurate copy of the time signal, and local faults should be easily discernable. Further signal analysis, such as those discussed in chapter 6 will reveal even more information about the machine element. However, this powerful noise reduction technique is not suitable for bearings because the position of the rolling elements relative to the raceways changes with each revolution of the race.

5.3.2. Bandpass Filtering (Frequency Windowing)[7,9,10]

Filters are used to suppress signals from random vibrations in comparison to periodic signals. It is also used to remove unwanted ringing effects caused by system or transducer resonances. In such cases the filter allows the initial peak registered by the transducer to pass, but attenuates the resulting damped response vibrations. It becomes clear that careful selection of filters is necessary to allow the signal and not the noise to pass.

Analogue analysers are in general being replaced by digital analysers based on FFT or digital filtering. this is because of its greater accuracy and increased flexibility. Using digital filtering allows the user to choose the required bandwidths precisely. A typical example is in the analysis of gearbox vibration spectra - here it is advisable to eliminate low harmonics by cutting off all frequencies below half toothmesh. This in itself does not improve the SNR, but is effective when used in conjunction with further spectral analysis techniques.

Another advantage in using digital analysis techniques is that if the system has a "zoom" capability, then the bandwidth can be chosen to suit the particular application. Hence the resolution of the signal can be selected to give an optimum SNR, since as one tries to define a signal more precisely in the time domain, its spread in the frequency domain increases, and vice versa. Another method of improving the SNR of signals makes use of resonances in a vibratory system. This is covered in Section 5.3.4.

When signals propagate through a system, their frequencies are modified, as well as their temporal characteristics. Removal of the contamination of the signal may be accomplished by linear filtering. However, this is not as simple as it sounds, since path and source effects are inextricably bound together during propagation. Thus eliminating the path characteristics in the frequency domain can defeat the objective if due care is not taken. The window is usually chosen at a frequency well above the low shaft orders to stay clear of excitation resulting from normal operation of the machine.

An alternative to frequency windowing is temporal linear windowing, or time gating. If part of a combined signal is separated from other arrivals in time, then gating enables one to separate the "n"th path from all the others. If the time delays in the paths are not sufficiently different it becomes difficult to perform this gating.

5.3.3 Adaptive Noise Cancelling[16]

Adaptive Noise Cancelling (ANC) is a method of estimating signals corrupted by additive noise. this method makes use of two inputs - a primary input containing the corrupted signal, and a reference input containing noise correlated with the primary noise. the reference input may be a sensor located at a point in the noise field where the signal is very weak, such as the base of a machine.

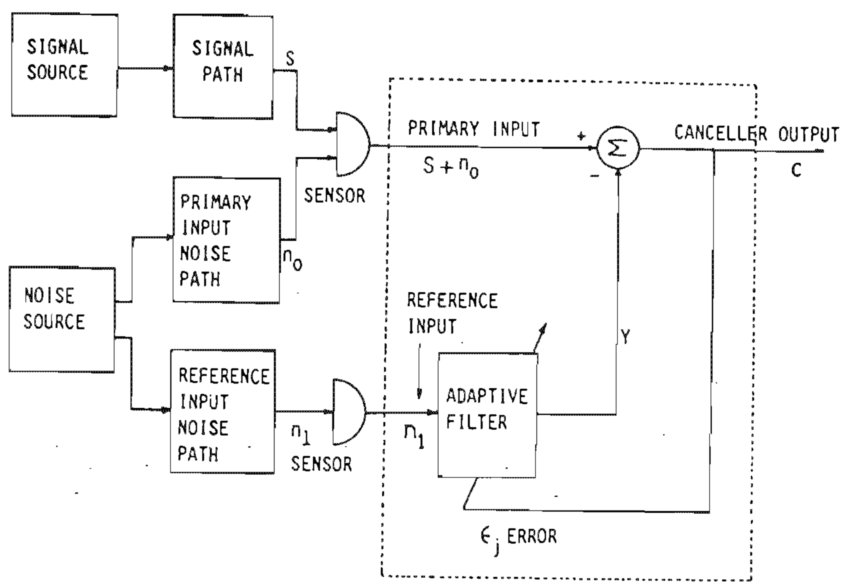


Figure 5.8 The Adaptive Noise Cancelling Principle

The general ANC principle is shown in figure 5.8. The signal S is corrupted by the noise n_0 and is received at the primary sensor. A reference noise n_1, is received at the reference sensor. This noise is related to the n_0 in an unknown way, but uncorrelated with signal S. The reference input is then adaptively filtered to match n_0 as closely as possible and is then subtracted from the primary input. the noise canceller output contains the signal plus residual interference. The adaptive filter acts to minimise the average power of the residual interference. The noise canceller output error signal is fed back to the adaptive filter and the filter characteristics are adjusted through a Least Mean Square adaptive algorithm to minimise the residual interference.

There are two situations where ANC is applicable. The first case is where the input noises are correlated. The second case is where the imputs contain correlated signals but uncorrelated noise. In both cases significant improvement in SNR can be achieved, and it has been shown[17] that prior to using ANC, diagnostic techniques such as kurtosis and power spectrum may not detect faults. Subsequent to using ANC, the background noise is effectively removed, enabling the successful application if diagnostic techniques.

5.3.4 High Frequency Resonance Technique (HFRT)[17,18,19]

This technique is also known as Demodulated Resonance Analysis, or Envelope Power Spectral Density Analysis. It is well suited to the vibration monitoring of gearboxes and turbomachinery because of its ability to separate the vibration generated by defective bearings from the vibration generated by other machine elements.

The principle behind HFRT is that whenever a defect in a machine element is excited, a short impulsive vibration is generated. Usually the energy from the pulse is distributed at a low level over a range of frequencies. However, the impact usually excites a resonance in the system at a much higher frequency than normal machine vibrations. Hence some of the energy is concentrated into a narrow band that is easily detectable. The resonance could be the ringing of damaged bearing races or even the transducer itself. The characteristic defect frequency is that of the occurrence of the impulse. Modulation of the resonance by the characteristic defect frequency makes it possible to detect the presence of a defect by the excitation of the resonance, as well as a diagnosis as to what part of the bearing the defect occurs.

The procedure for HFRT is as follows: The accelerometer signal is amplified, and sometimes low-pass filtered to attenuate the transducer resonance. The signal is then bandpass filtered around the resonant frequency to eliminate background noise or other resonances. The remaining signal consists of a narrowband carrier at the resonance frequency, amplitude modulated at the characteristic defect frequency. The characteristic defect frequency is then extracted by envelope detection, in which the signal is rectified and smoothed to eliminate remaining noise components. All that then remains is to analyse the envelope signal.

An alternative approach to HFRT is to omit the low pass filter and allow the accelerometer resonance to amplify the signal. The accelerometer is considered as part of the system which resonates. Its ringdown pulses are demodulated and smoothed, yielding a pulse train with the same repetition rate as the flow impacts. An advantage is that amplification is provided at the accelerometer resonant frequency, improving the SNR. A disadvantage is that impulses from other machine elements may also excite the accelerometer and produce misleading results.

5.3.5 Cepstrum Analysis[10,15,20-24]

The cepstrum, which derives it name from "spectrum", has been defined in a number of different ways. They can all however, be considered as a spectrum of a logarithmic spectrum i.e. logarithmic amplitude with linear frequency scale). Essentially, it is obtained by conducting a frequency analysis of a spectrum. Thus it can be used as a tool for the detection of periodicity in a spectrum, such as families of harmonics with uniform spacing. The logarithmic amplitude scale emphasises the harmonic structure of the spectrum and lessens the influence of the transmission path effects.

The type of periodic effect is often found in the sidebands commonly found in gearbox vibration spectra, and often indicate faults of various kinds. Here the cepstrum provides a diagnostic aid in interpreting spectral information. It is also useful as a data reduction technique, effectively reducing a whole family of sidebands into a single line in the cepstrum, simplifying the problem of monitoring change in machine condition.

One of the more recent definitions of the cepstrum is "the inverse Fourier transform of the logarithm of the power spectrum", or mathematically

$$((\tau) = F^{-1} \{ \log P(f) \} \qquad (5.7)$$

where $P(f) = | F \{f(t)\} |^2$ (5.8)

It should be noted that the independent variable τ of the cepstrum has the dimensions of time, but is known as quefrency. Where peaks in the cepstrum result from families of sidebands, the quefrency of the peak represents the periodic time of the modulation, and its reciprocal the modulation frequency. The quefrency says nothing about absolute frequency, only about frequency spacings.

In normal vibratory situations, the measured power signal at an external measuring point is the product of the source function and frequency response function of the transmission path. (see equation (5.6b). The effect of taking the logarithm is to transform the multiplication into an addition:

$$\log X = \log H + \log P \qquad (5.9)$$

The additive relationship is maintained by the inverse Fourier transform i.e.

$$F^{-1}(\log X) = F^{-1}(\log H) + F^{-1}(\log P) \qquad (5.10)$$

The left hand side of this equation is the same as the cepstrum (equation (5.7), which means that the source and transmission path effects are additive in the cepstrum. Since they often have quite different quefrency contents, they will be separately shown in the cepstrum. The application of cepstrum in gearbox fault diagnosis is discussed further in Chapter 6.

5.3.6 Enveloping[19]

A full or half-wave rectifier is used to convert a band-passed bipolar time signal to a unipolar output, followed by a peak-hold smoothing circuit. The decay portion of the envelope is of little use in the analysis of the enveloped signal, since it is the repetition rate indicated by the peaks that is of interest.

The selection of the time constant for the smoothing circuit is of importance. If too long, the decay will be too slow and small peaks may be buried in the decay of a preceding large peak. If too short, a carrier ripple will remain in the signal, requiring further smoothing. fortunately the expected shape of the signal has a sharp initial rise followed by exponential decay, allowing the smoothing circuit to be matched with it. The signal can then be processed for further analysis.

5.3.7 Applying SNR Techniques

The application of the above techniques for improving the signal to noise ratios of vibration signatures depend on individual conditions. In some cases they will not be necessary, while in others it would be impossible to make any fault diagnosis without them. Careful attention must be paid to the type of information carried in the signal, as the incorrect application of noise reduction technique could reduce or remove the signal to such an extent that fault diagnosis would prove unsuccessful.

In some applications it is useful to apply two or more of the noise reduction techniques described here. For example Adaptive Noise Cancelling or Bandpass Filtering can be used prior to Cepstrum analysis[18]. Again it depends on the characteristics of the signal that is being analysed (such as impulsiveness or harmonic frequencies). Cepstrum analysis in itself is a powerful analytic tool in vibration analysis and will be discussed further in the following chapter.

6. FAULT DIAGNOSIS IN VIBRATING MACHINERY

Numerous diagnostic methods exist for the diagnosis of faults in vibrating machinery from signal analysis techniques. With the increasing use of computers, these methods have improved, while new methods are constantly being devised, tested and implemented. Due to the widely differing characteristics of rotating machinery, and the multitude of possible types of failure, it is difficult to establish which one is the correct method of diagnosis to apply. The consequences of various types of faults will usually determine which method to use, and what degree of sophistication to employ. Often under adverse conditions it is the combined evidence of a number of techniques that enables damage to be detected.

Generally speaking, the diagnostic techniques can be classified in terms of the types of machines to which they are applicable. The most common applications are in bearing fault detection and gear defect monitoring and diagnosis. Clearly some of the diagnostic methods will be suitable for application to different classes of machines, due to the different characteristics of vibrations emanating from machinery. The selection of the machine monitoring method is usually done by the maintenance engineer or production manager after careful consideration of the factors involved. This chapter deals with the diagnostic techniques available for fault finding in vibration analysis. Fortunately some of these techniques produce a binary outcome of the machine's condition: either a fault exists or it doesn't. What about those techniques that produce answers that indicate a fault is present, but do not necessarily indicate that the machine should be stopped and repaired?

In such a case the limiting conditions of the monitored parameter could be chosen as[25]:

(a) A maximum rate of change
(b) A maximum deviation from a reference level
(c) An upper limit

These conditions can all be easily monitored by graphical trend analysis of the monitored signal(s). On a parameter-time graph the limiting conditions become:

(a) A maximum permissible slope
(b) A maximum deviation from a reference level
(c) A fixed upper limit

Thus the advantage of a graphical record can clearly be seen, and since large quantities of data are involved, computers are becoming more and more common in condition monitoring systems.

6.1 TIME-BASED DIAGNOSIS

This is the simplest technique and requires only elementary knowledge of the monitored machine. The time history signature could reflect displacement, velocity or acceleration and is suitable for fault diagnosis in bearings, gears and even reciprocating machinery.

A relatively new concept of using displacement transducers is discussed in reference[26]. Most previous methods are based on velocity or acceleration measurements. The advantage of the displacement tranducer method is that provided the signal is synchronized with the shaft rotational speed, the exact location of damage to either the inner or the outer race can be determined. Inner race damage is more difficult to interpret since the damage signals do not repeat with every ball passing cycle. since the frequency of the fault can be calculated, damage can easily be traced to its source by referring to table 6.1[10]. Chatuverdi and Thomas[16] have shown that by applying Adaptive Noise Cancelling to vibration signatures corrupted by turbine noise, defective bearings can be easily identified. Since signal averaging cannot be applied to bearings, this is a powerful tool for the diagnosis of defective bearings under adverse conditions.

A similar method can be used for monitoring gear trains. The gears mesh at a specific frequency, and thus observation of a once per revolution marker and the pulse on a dual channel oscilloscope can reveal the location of the defective tooth with respect to the marker. By using signal averaging, the condition of individual gears in a gearbox can be assessed by synchronising the analyser with the speed of each gear in turn (see figure 6.1).

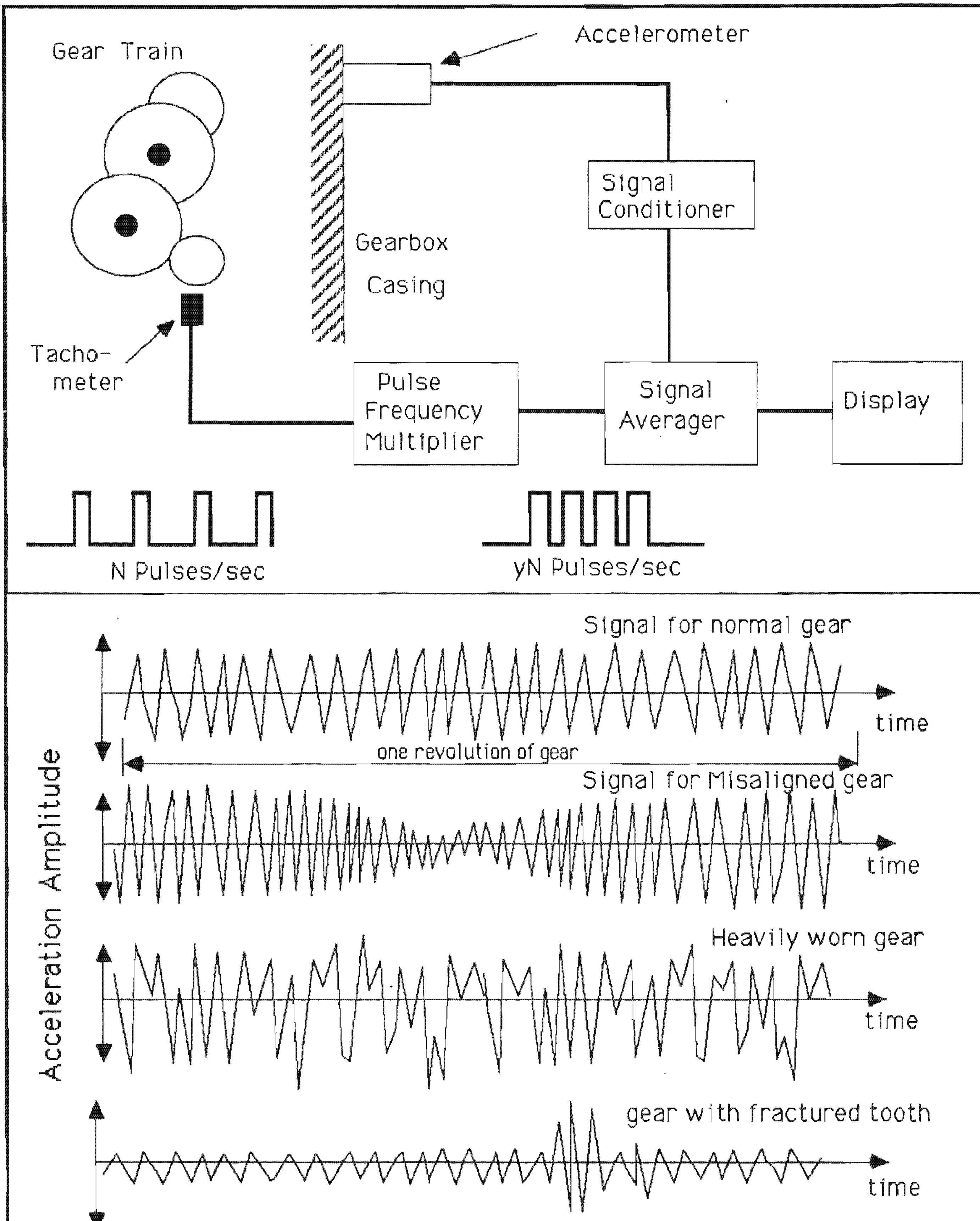


Figure 6.1 Signal Averaging Applied to Gearboxes

Condition monitoring of reciprocating machinery presents many problems to the machine analyst. The common techniques of harmonic and r.m.s. measurements cannot be used in a straightforward manner when applied to reciprocating machines[16,22]. The reason is that the working cycle consists of many transients of short duration caused by piston-cylinder impacts, pressure pulsations and valve operations (ie. noise). Thus time domain analysis is an essential part of reciprocating machine monitoring. Functions of pressure and vibration are good indicators of machine condition when displayed together as a function of crank angle. The pressure trace rapidly reveal the condition of the valves in individual cylinders. Averaged vibration signals with time windows centred on individual component events can sometimes reduce noise sufficiently to enable faults, such as valve oscillations, to be detected.

Sometimes the time signals themselves are used to indicate machine condition, by statistically analysing the signal and producing a one-figure representation of the severity of the vibration. The simplest of these approaches is the overall Root Mean Square level, and is the basis of some standards for evaluating vibrations. These are of limited value since it has been shown that in the early stages of damage the overall level may not be affected[27], or may not change at all[28]. Nevertheless they are useful for simple systems or where other information is totally absent, so this approach cannot be totally disregarded.

6.2 STANDARDS FOR EVALUATING OVERALL VIBRATION LEVELS

A number of standards exist for the evaluation of vibration levels in machinery[11,29]. The British Standard BS 4675 mentioned in Chapter 5.2.3., is designed to assess the general condition of a machine. Therefore it cannot be applied as criteria in relation to plant condition monitoring since the criterion bands are wide to allow for production spreads in tolerances. Moreover, standards apply to "average" machines, and no fixed definition exists to describe what "average" is. It seems that defining the machines covered by standards is a major point in determining their accuracy. Since this is achieved in different ways in the different standards, their authenticity is questionable.

A more reliable method is to use the vibration level(s) when the machine is in good condition as a reference. The machine condition is then judged by the departures from these original patterns. This is where the standards are in good agreement i.e. by removing the significance of absolute vibration levels. An increase of between 6 and 8 decibels is considered significant, while a change of 20 dB is serious. It should be borne in mind that equal increases on a logarithmic axis are also serious, since this in effect represents an exponential deterioration.

This indicates that trending of vibration data should be performed, using a standard to determine which are tolerable increases. The point in question is then: Which parameter should be monitored? It is not unusual to carry out trend monitoring of overall (eg rms) vibration levels, one of the advantages being that these are relatively stable and exhibit less spread than individual components in vibration spectra. Another reason is that only one measurement for each transducer is required. Alternatively octave of 1/3 octave band level analysis may be performed, but the increased sensitivity of such methods means that more measurements are required. This could prove a major factor when large numbers of machines are being monitored.

As mentioned previously, vibrations may be measured in terms of acceleration, velocity or displacement. For a given frequency f, these parameters are simply separated by a factor of $2\pi f$. It thus becomes a simple task to integrate a given signal from an accelerometer either by analogue or digital conversion, to produce velocity or displacement. Overall r.m.s. velocity is considered to be the most useful measure for total vibration monitoring and is used in various standards in the frequency range 10 - 10000 Hz[11,29]. When continuous monitoring is employed, the processed signal is usually displayed on a chart recorder, while the equipment may be arranged to trigger alarms at a predetermined signal level, change in level or rate of change in overall level[30].

6.3 FAULT DIAGNOSIS USING NARROWBAND VIBRATION SPECTRA

In many situations a change in the level of one particular component may grow for several months before it influences the overall level, if at all. In such circumstances frequency analysis is essential, while overall total signal monitoring may still be done.

VIBRATION TROUBLE SHOOTING CHART

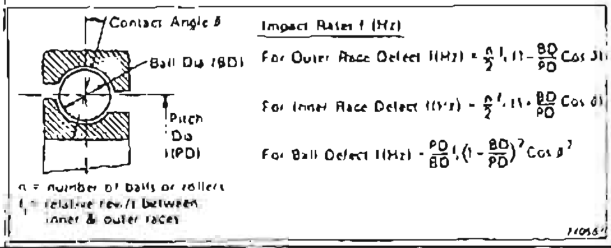
Nature of Fault	Frequency of Dominant Vibration (Hz=rpm/60)	Direction	Remarks
Rotating Members out of Balance	1 x rpm	Radial	A common cause of excess vibration in machinery
Misalignment & Bent Shaft	Usually 1 x rpm Often 2 x rpm Sometimes 3&4 x rpm	Radial & Axial	A common fault
Damaged Rolling Element Bearings (Ball, Roller, etc.)	Impact rates for the individual bearing components* Also vibrations at very high frequencies (20 to 60 kHz)	Radial & Axial	Uneven vibration levels, often with shocks. *Impact-Rates: 
Journal Bearings Loose in Housings	Sub-harmonics of shaft rpm, exactly 1/2 or 1/3 x rpm	Primarily Radial	Looseness may only develop at operating speed and temperature (eg. turbomachines).
Oil Film Whirl or Whip in Journal Bearings	Slightly less than half shaft speed (42% to 48%)	Primarily Radial	Applicable to high-speed (eg. turbo) machines.
Hysteresis Whirl	Shaft critical speed	Primarily Radial	Vibrations excited when passing through critical shaft speed are maintained at higher shaft speeds. Can sometimes be cured by checking tightness of rotor components.
Damaged or worn gears	Tooth meshing frequencies (shaft rpm x number of teeth) and harmonics	Radial & Axial	Sidebands around tooth meshing frequencies indicate modulation (eg. eccentricity) at frequency corresponding to sideband spacings. Normally only detectable with very narrow-band analysis.
Mechanical Looseness	2 x rpm		
Faulty Belt Drive	1, 2, 3 & 4 x rpm of belt	Radial	
Unbalanced Reciprocating Forces and Couples	1 x rpm and/or multiples for higher order unbalance	Primarily Radial	
Increased Turbulence	Blade & Vane passing frequencies and harmonics	Radial & Axial	Increasing levels indicate increasing turbulence
Electrically Induced Vibrations	1 x rpm or 1 or 2 times sychronous frequency	Radial & Axial	Should disappear when turning off the power

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Table 6.1 Diagnostic Chart

When the frequency of vibration associated with a maintenance problem is known in advance, frequency analysis provides useful information as to the cause of the problem. Table 6.1 lists a number of faults and the way in which they can be diagnosed with respect to their frequency and direction of maximum expected motion. Frequency monitoring is not always as straightforward as is suggested here and can usually only be effective after gaining experience with a particular machine. The tell-tale frequencies of machines may not appear to indicate faulty conditions, but trend analysis of such components would be sure to highlight any worsening machine condition.

6.3.1 Harmonic Components

Gearbox vibration spectra generally exhibit a fundamental frequency, corresponding to toothmeshing rate, in the form of a distinct line in the spectrum. Higher order harmonics of the fundamental will also be found, but these components decrease in magnitude with increasing frequency. Under constant load, any changes in the toothmeshing frequency and its harmonics would most likely be due to wear, which usually occurs as the result of the sliding action between the teeth (there would not be as much wear on the pitch circle since at that point there is only rolling contact between gear teeth). The resulting profile error would tend to give considerable distortion of the toothmeshing frequency, and thus wear is often more evident at the higher harmonics of toothmeshing than at the fundamental frequency itself (Figure 6.2). It is usually sufficient to monitor the first three toothmeshing harmonics to detect tooth wear.

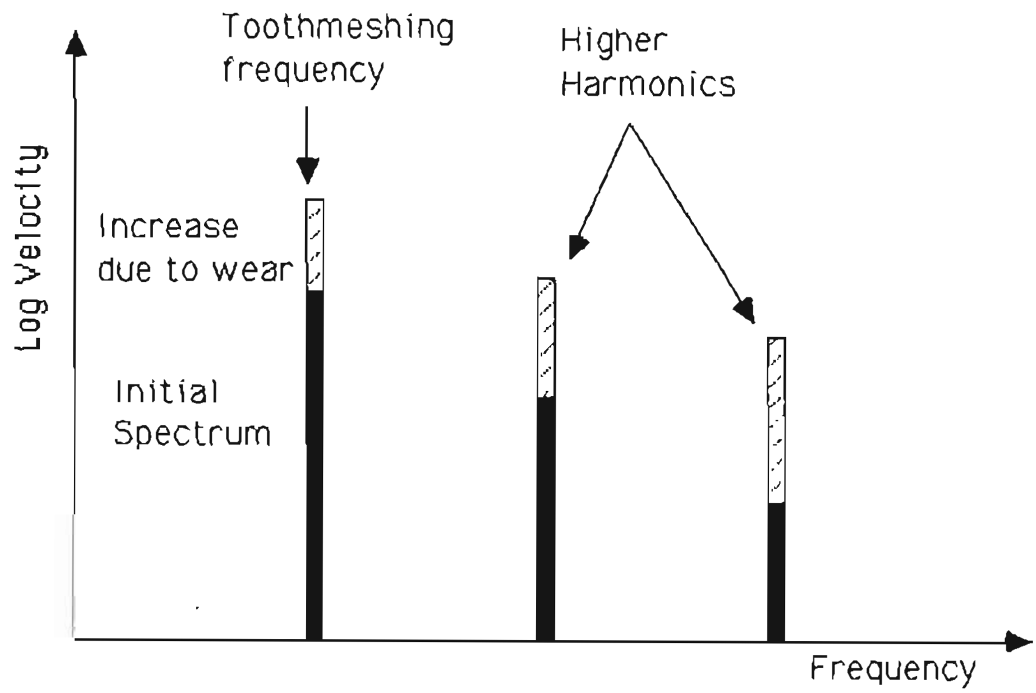

Figure 6.2 Typical Vibration Spectrum changes due to wear

Other phenomena that are sometimes observed in gearbox vibration spectra are intermodulation components[31,32] and ghost components[15,23]. Intermodulation Components arise due to sum and difference frequency effects of the major frequency components. Once recognised, such components do not give grounds for concern, as they would normally only change as a result of changes in the fundamental components.

Ghost components arise from errors in the teeth of the index wheel used for machining the gear. The frequency later generated by the gear in service corresponds to this number of teeth and therefore must be an integer harmonic of the gear rotational speed. Another indication of a ghost component can be obtained from its insensitivity to load effects. Once recognised, ghost components do not usually cause problems, and they tend to become smaller with time and wear.

Bearing harmonics are not as straightforward to monitor due to intermodulation between characteristic bearing frequencies. Another problem is that the vibration signature of a badly damaged bearing closely resembles that of a bearing in good condition, except that the level is much higher[9,18,33].

A useful method has been suggested by A.R. Ray [Ref. 3] for detecting bearing failure using a simple manipulation of vibration spectra. The vibration signal is bandpass filtered, then enveloped to crudely demodulate the band passed signal before power spectrum analysis. Two signals are used. One is normalised by dividing the standard deviation of the input signal. The other is raised to the fourth power subsequent to band pass filtering. The philosophy behind the method is this: If in the power spectrum of the envelope of this signal the peak at rolling element past outer race frequency decreases relative to background energy levels, then the modulation is assumed to be sinusoidal and the bearing undamaged. On the other hand the pattern of a damaged bearing will be distinctive, exhibiting definite harmonics at the characteristic frequency of the fault. However, under adverse conditions this method is not appropriate, and an analysis system using noise cancellation and matched filtering must be used.

6.3.2 Side Band Analysis

Sometimes there is an absence of significant peaks at the fundamental frequencies, indicative of a particular defect of the gear or bearing. In such cases power spectrum technique fails to detect and diagnose mechanical defects. Despite the absence of these peaks, Osuagwu and Thomas[41] have shown that fault detection and diagnosis is still possible. The discriminant feature used to detect a defect is a characteristic doublet structure present only in the defective power spectrum (figure 6.3). These doublet structures occur at frequencies harmonically unrelated to the fundamental impact frequency (FIF), but with a recurrence of this structure at every fundamental impact frequency. The periodic recurrence of the doublet structure is found to carry source identification information.

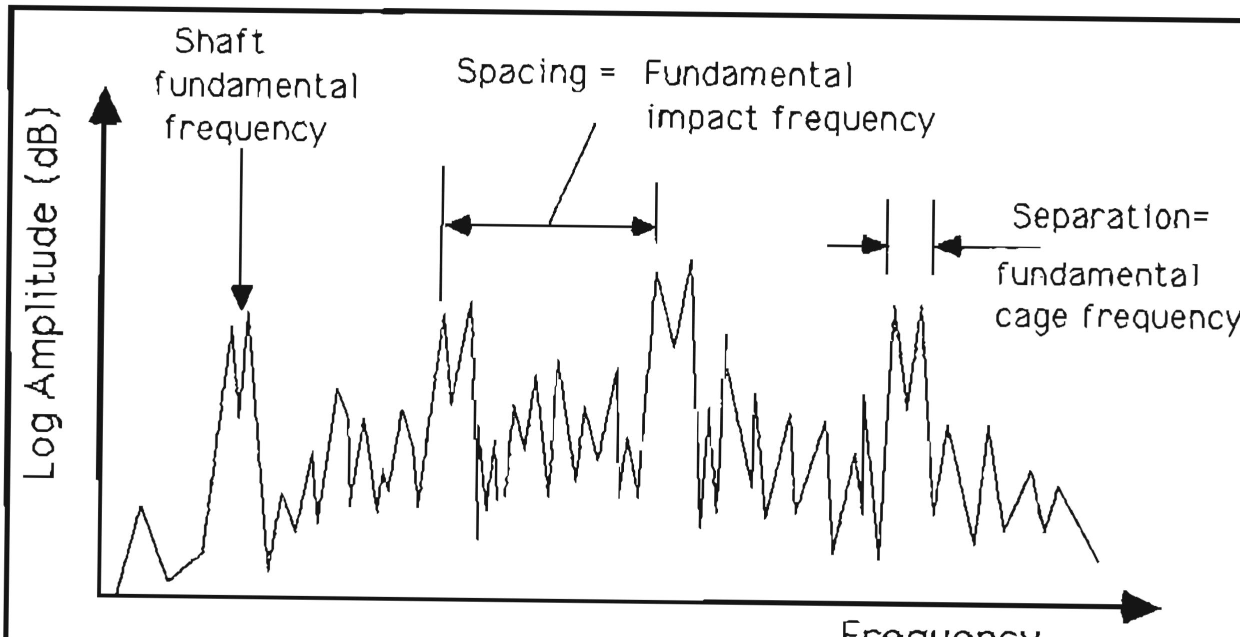

Figure 6.3 Damaged Bearing Vibration spectrum showing occurrence of Doublet

The absence of a significant peak at the FIF is due to two causes which may operate simultaneously:

1. An average and shift effect produced by a quasi-periodic instability or the rapid variation of the impact rate in the waveform. This may cause a slow migration of the fundamental impact frequency from its computed value.

2. An intermodulation effect which translates defect related information to frequency locations unrelated to the fundamental impact frequency.

In the study by Osuagwu *et al* ball bearings were used. It was found that over all operating conditions defective spectra show characteristic doublet structures with a base corresponding to shaft frequency, and a recurrence of the doublet at every fundamental impact frequency. In particular the peak of the first doublet frequency band was found to be very sensitive to defect onset and growth.

Although this study only dealt with ball bearings, it has been shown that a similar doublet structure will occur for gears with eccentricity or shaft misalignment[14]. The doublet is essentially a fundamental frequency (gear mesh) with sidebands at plus and minus shaft speed rotation.

Modulation effects, which are easily detected using time signal analysis, are also shown up in frequency spectra. A localised fault, which will appear as a single peak in the time domain, is reflected as a single peak in the frequency domain with similar smaller harmonic components. A distributed fault on the other hand shows amplitude and frequency modulation in the time domain. The broader the envelope of the fault in the time domain, the narrower and higher the envelop of the sidebands in the frequency domain, so that they will more obviously appear as sidebands around the toothmeshing harmonics. Thus the additional effect of frequency modulation is to increase the number of sidebands.

6.4 THE CEPSTRUM AS A DIAGNOSTIC TOOL

The Cepstrum is an effective aid for detecting the periodicity in a spectrum, such as families of harmonics with uniform spacing. Since it is derived by manipulating spectral information, the cepstrum is often used in conjunction with its corresponding spectrum when analysing vibration information. Each plays a complementary role, since the spectrum is suited to the detection of faults while the cepstrum is more useful for fault diagnosis. Although the cepstrum is best suited for gearbox fault diagnosis, applications have been found for monitoring bearings[31] and reciprocating machines[24]. However, it is conceivable that it can be used for analysis of any type of vibration that exhibits periodicity.

Amplitude and frequency modulation in gears seldom occur separately, and to distinguish between them is extremely difficult based on the spectrum alone. These modulations give rise to sidebands in the spectrum, and the spacing between them gives the fundamental modulating frequency. This modulating frequency is usually sufficient to trace the source. By establishing the sideband spacing, the cepstrum is thus capable of establishing the cause of the fault.

The cepstrum also has a strong normalising effect that is insensitive to extraneous effects that give significant variations in sidebands. One of these is signal transmission paths which can give large differences in spectrum shapes from one point to another. As pointed out in Chapter 5 the cepstrum separates source and path effects (transfer function) which usually dominate the low quefrencies (high frequency) and are therefore well separated from the source information.

Another advantage is that a peak in the cepstrum represents the average sideband spacing based on the whole spectrum range, rather than the spacing between just two or three. This improves the accuracy of the diagnosis. In reference 23 a spectrum analysis of a truck gearbox shows a number of sidebands spaced at approximately 100 ms (10Hz). Initially it was suspected that this was the second harmonic of the engaged first gear rotating at 5.4 Hz. A cepstrum analysis shows a dominant 95.9 ms (10.4 Hz) component corresponding exactly to the second gear speed and indicating that this was the modulating source, even though it was idling.

To sum up, the cepstrum has advantages based on the following:

(a) Its ability to detect spectrum periodicity not apparent to the eye.
(b) The fact that it represents an average spacing over the entire spectrum.
(c) Its lack of sensitivity to extraneous effects not directly related to source information.
(d) Its complementary role with spectral analysis, allowing for detection and evaluation of sidebands due to modulation of vibrations.

6.5 STATISTICAL PARAMETERS IN FAULT DIAGNOSIS

Vibration signals obtained in condition monitoring contain an enormous amount of information about the machines that produce them. Techniques have thus been devised to process the signals to highlight certain aspects of the total signal by manipulating the data contained in them. Although computers can be used to produce large amounts of information from the signals, it is preferable to produce as little data as possible, but at the same time accurately reflect machine conditions. Consequently a lot of work has been done to establish which statistical parameters are most sensitive to machine condition, thus simplifying monitoring, and allowing comparisons between similar machines to be made. Without going into too much depth, the more effective parameters will be outlined below, with references to papers where the techniques have been tested and evaluated.

6.5.1 Trend Parameters[6,34]

As mentioned in Chapter 6.2, r.m.s. level monitoring is a useful general purpose method of monitoring machinery. On a rms-time curve vibration severity can be estimated by checking the deviation from a reference level, a rate of change or a maximum level. This sort of monitoring can be refined by establishing parameters that combine the effects of such changes as follows[34].

(a) MFO - matched filter r.m.s. based on original spectrum.

(b) RDO - r.m.s. of difference in spectrum between each successive data set and the original

(c) MFP - matched filter r.m.s. with respect to the previous signal.

(d) RDP - r.m.s. of difference in spectrum between each successive data set and the previous.

In reference 6 it is shown that MFO and RDP give consistently good detection of failure. Of the two, MFO showed distinct increases in slope at the point of failure in bearings followed by levelling off as damage progressed.

6.5.2 Probability Functions[12,34-36]

The amplitude characteristics of a vibration signal can be expressed in terms of an instantaneous probability density function p(x). This is estimated by determining the duration a signal remains in a set of amplitude windows. For a stationary random process a logarithmic probability scale enhances changes at low probability and the density function is an inverted parabola, indicating a Gaussian distribution. Any nonlinearity in the signal causes a symmetry of the curve. With increasing time and damage the tail of the distribution curve broadens, and the peak becomes "spiky". This characteristic can be enhanced by taking the probability density curve to give the probability of exceedence. This provides information on the probability of the signal exceeding any particular amplitude, and can thus be used to detect peaks in a signal.

6.5.3 Statistical Moments[34,35]

A series of statistical moments can be used to indicate the shape of the probability density distribution and these are defined by the general integral:

$$M_n = \int_{-\infty}^{+\infty} x^n \; p(x) \; dx \qquad\qquad n = 1, 2 \ldots m$$

The first and second of these are well known: n = 1 gives the mean level and n = 2 the mean square. Odd moments relate information about the position of the peak density relative to the median value. For a symmetrical distribution they should be close to zero. Even moments indicate the spread in distribution. Moments can be normalised by removing the mean and dividing by the standard deviation raised to the order of the moment. The third central moment (n = 3) is defined as skewness, while the fourth moment (n = 4) is defined as kurtosis.

Kurtosis represents a compromise measure between insensitive lower moments and over-sensitive higher moments. For an undamaged bearing it remains close to 3. Impending failure is usually indicated for kurtosis values over 5 but it may vary between machines. Reference 35 shows that instead of determining overall levels, kurtosis observed over selected frequency bands yields more information, and that with increased damage kurtosis increases in the higher frequency bands.

In reference 34 it was found that a consistent parameter for detecting impulsiveness is the product of r.m.s. and kurtosis levels since they are sensitive to overload and impulsiveness respectively. Since impulsive vibrations can be observed on bearings suffering from fatigue and spalling damage, this method is often used.

Although an ultimate time to failure cannot be accurately predicted with kurtosis, it has been used to good effect in numerous cases and has several distinct advantages[5,16,19,22,26,37]:

- insensitive to load and speed
- predicts the severity and extend of damage
- applicable to most types of machinery
- no previous history required.

6.5.4 Crest Factor Analysis and Shock Pulse Monitoring

Two other methods that have been used to good effect for monitoring bearings are:

(a) Crest Factor Analysis
The ratio of peak level and r.m.s. level has been found partially insensitive to bearing load and speed. Since impulsive signals exhibit large peaks, this method is advantageous, especially since minimal recourse to previous history is required[34].

(b) Shock Pulse Monitoring
A system using a high frequency response piezo-electric accelerometer to sense the compression wave created by impacts on the bearing has been developed in Sweden and marketed as an SPM meter. The initial response of the accelerometer is directly proportional to the impact velocity and thus indicates bearing condition. Normal shock values relating to shaft speed and diameter are calculated, and then used as a bench mark to compare all readings with[8,7,17].

6.6 SUMMARY

This chapter outlines some of the methods used for fault diagnosis in vibrating machinery. Some of the methods are more effective than others, but they all have some value since different machine faults are highlighted in different ways. Although most of the techniques in use today have been discussed, these are by no means all the ones available.

Vibration monitoring in preventive maintenance is a relatively new field and new methods are continually being devised and evaluated. In order to go about implementing vibration analysis in preventive maintenance, it is necessary to approach the task in a systematic way. It will usually take a few years of learning time while experience is gained and the correct methods are selected. A knowledge of the machine and their operation is essential. Often it will require two or more diagnostic techniques to cover all types of failure on a particular machine. Selection of equipment must be done with care to make efficient use of it since it is expensive. The increasing use of computers is a promising line of development, enabling multiple sources to be used for data input and interpretation.

7. SETTING UP FOR CONDITION MONITORING

7.1 SELECTING THE METHOD OF MONITORING

Selecting the method of monitoring plant and equipment is not an easy task. Usually more than one condition monitoring method can be used for each machine or component. For example roller bearings can be monitored by magnetic plug detectors, temperature measurement or vibration analysis. Vibration monitoring is possibly the best of these methods, since it is applicable to all moving machinery and there are numerous methods available for detecting different types of fault in different kinds of machinery. Since the setting up procedures for vibration analysis are the same as for other condition monitoring procedures, this chapter refers to condition monitoring in general.

Particularly critical machines might warrant multiple or special techniques to prevent major disruptions and enable comparative guidance for important shut-down decisions. The final judgement on which machines to monitor and by which method, is left up to the senior engineer concerned to choose. Help could be obtained from a consulting company which would advise on the best method(s) to use and how to go about implementing them. Alternatively contractors could be employed to do the monitoring, providing condition monitoring services and eliminating the need for expensive equipment. Organisations of this kind can gain extensive experience in many different fields. This is a viable alternative for small companies, but in larger companies it is often preferable to set up an in-house monitoring programme.

7.2. SELECTING MACHINES AND COMPONENTS FOR MONITORING

It is essential when selecting machines for condition monitoring to obtain a flow diagram for the production process. This will illustrate which machines are critical to maintain production. These are usually ones which:

- are in continuous operation
- are involved in single stream process
- have minimal stand-by capacity
- have a history of problems
- have minimum product storage capacity

Important factors in machine selection which must be taken into account are the risk of consequential damage or hazards to personnel. Once the machines for monitoring have been selected, it is then necessary to decide what critical failures are likely to occur and match these to suitable monitoring methods on a cost-effective basis.

Failures originate in particular components, and so the monitoring method must be matched to the components to achieve maximum sensitivity. An effective technique for determining a priority rating for components is to rate them from 1 - 5 in terms of failure as follows[1,7]:

(a) likelihood
(b) consequence
(c) repair time

By multiplying the figures together a priority rating of between 1 and 125 is obtained.

7.3. INTRODUCING CONDITION MONITORING

Moving to condition based maintenance from routine preventive maintenance usually takes about two to three years. This is largely due to the time required for making the correct interpretation of measurements, and to learn to analyse the data correctly.

A convenient way of introducing condition monitoring is to purchase simple measuring instruments and use them to take readings on the plant just before regular maintenance shut-down. By inspecting for damage, experience can be gained linking condition characteristics to faults or damage.

The personnel who are to handle the condition monitoring program have to be educated and trained. It is preferable that they are already employed in plant maintenance, allowing previous experience to help in diagnosing faults and irregularities. Experience has shown that by identifying themselves with a project, personnel become motivated to obtain positive results. Tasks are usually divided. One or more persons perform the actual vibration measurements by following standard procedures, after which a technician or engineer evaluates the results to detect faults. If fewer than 50 monitoring points are analysed per month, the engineer can perform the whole operation himself. As the number of monitoring points increases, automatic computer-based spectrum analysis systems become attractive. Several users could share such a system or it could be utilised by several plants in the same organisation.

Measuring points must be selected to yield useful measurements. National or international standards can sometimes offer additional guidance. Measurement points must be numbered and prepared for easy attachment of the transducers by clearing surfaces and providing attachment studs for permanent fixing points.

The average operating time between failure for a machine dictates the periodic measurement intervals. At least six measurements should be planned for this period to give a reasonable predictive ability. For new machines where guidance is not available from the manufacturer, fairly frequent monitoring should be performed until experience is gained.

7.4 KEEPING RECORDS

An essential feature of condition monitoring, whatever the technique, is the accumulation of data and record keeping. Various instrument settings should be standardised for each machine, since measurements will only reveal trends if they are made under the same conditions. Details of the dynamic characteristics like shaft speeds, numbers and dimensions of bearings and gearbox data must be recorded on a master card for each machine. This enables a diagnostic reference diagram to be drawn up so that various frequency components can be related to specific machine parts.

Where the trends in a monitored parameter are used to indicate plant condition it is useful to plot the data directly onto graphs since the mind can absorb visual data more effectively than written data. This also reduces the paperwork required. Unfortunately there is considerable redundancy in measurements in the early stages of a monitoring programme. After experience has been gained, the engineer will be able to decide to cut down on the number of measurements made.

Where monitoring methods produce single-figure results indicating machine condition, a successful technique for evaluating condition is to monitor trends in parameter levels. Such condition curves often take the bath-tub shape of failure probability curves - initially the monitored parameter decreases during run-in, maintains a steady level during normal life and then increases exponentially towards ultimate failure (fig. 2.1.A). Once the condition curve starts to increase, the graph can be exponentially extrapolated to estimate the lead time to failure by setting limiting conditions on the parameter. At this stage the period between measurements must be reduced to keep a close watch on the component. The measurements will also need to be analysed to ascertain which component is the cause of the deterioration i.e. the irregularity must be diagnosed as soon as possible. Such a monitoring system proves ideal for the application of a personal computer to manipulate the data.

7.5 COMPUTERS AND CONDITION MONITORING

A computer can greatly simplify data handling and storage in a condition monitoring program. The data could either be typed in manually or read in via an interface. Software has been developed for comparison purposes and trend extrapolating to determine the estimated lead time to failure.

Computers are particularly suited to vibration analysis due to the many functions they can perform. Perhaps the most important is the Fast Fourier Transform (FFT), which is an efficient way of calculating the fourier transform of a time series i.e. a computer algorithm for calculating discreet Fourier transforms from digitised time signals. The following functions can also be performed:

- frequency analysis
- spectrum comparison
- fault detection and diagnosis
- cepstrum analysis
- time domain averaging
- statistical data evaluation
- permanent monitoring
- data handling

As experience is gained and benefits become apparent, the condition monitoring programme will gain credibility amongst personnel and management, and the programme can be expanded to suit individual requirements and achieve even better results as more experience is gained.

8. SUMMARY

By outlining the role of condition monitoring, and more specifically vibration analysis, in predictive maintenance this thesis emphasizes the growing importance of these techniques for the efficient running of production plants. The use of vibration analysis in machine health monitoring is shown to be an effective diagnostic tool if handled correctly. Since no literature that illustrates the use of modern diagnostic techniques in preventive maintenance has been found, this dissertation is intended to bridge that gap. It explains what vibration analysis entails and how it can be used to detect and diagnose many different types of fault in vibrating machinery.

A brief mention is made of the approach to introducing condition monitoring to existing maintenance programs. This is in itself a large and involved topic, and it is suggested that further work be carried out in this field.

To sum up, condition monitoring programs, and more specifically vibration analysis can be justified in terms of the following:

1. Increased plant safety
2. Reduced maintenance costs
3. Extended machinery life
4. Improved machine availability
5. Improved product quality
6. Lower insurance costs
7. Increased profitability

Of the three main types of condition monitoring methods available, vibration monitoring is the most versatile and is essential for an effective predictive maintenance programme. With the increasing threat of sanctions against South Africa predictive maintenance is destined to play an ever increasing role in efficient maintenance management in local industry.

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